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GATING AND CONTRAST-MODULATION RELATED TO ACTIVE
COVERT NIGHT PHOTO SYSTEMS

Bruno K. Wernicke

Air Force Avionics Laboratory
Wright-Patterson Air Force Base, Ohio

May 1975

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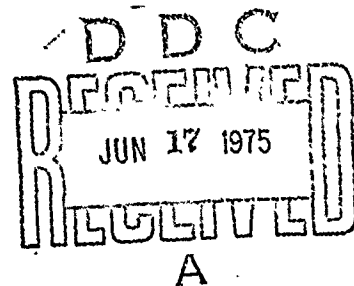
GATING AND CONTRAST-MODULATION RELATED TO ACTIVE COVERT NIGHT PHOTO SYSTEMS

TECHNICAL REPORT AFAL-TR-74-212

MAY 1975



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This technical report has been reviewed and is approved for publication.

Albert W. Berg, Chief
Reconnaissance Sensor Development Branch
Reconnaissance and Surveillance Division

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) An investigation was made to compare the improvement of contrast modulation for different degrees of gated and non-gated Active Night Photo Systems. Illumination sources and sensor are near the same location. The effects of the atmospheric backscatter on the contrast modulation received by the imaging sensor was determined in steps from a fully gated to a non-gated situation. Characteristic curves were derived for several flight altitudes from 2,000 to 23,000 feet and atmospheric conditions of meteorological		

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visibility of 23 Km and 5 Km representing an upper and a lower limit for the most frequently occurring conditions. Specific regions where the contrast modulation decreases at higher rates are shown.

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FOREWORD

This technical report was prepared by the Reconnaissance and Surveillance Division, Air Force Avionics Laboratory. The investigations were accomplished under Project 20040528, "Photographic Sensor and Concept Investigations." The author, Bruno K. Wernicke, was the investigator in charge of a trend study concerning the effectiveness of, and the need for, gating with regard to contrast modulation, atmospheric conditions, and flight altitudes.

The atmospheric effects and the influence on the discussed contrast modulation is based on the statistical tables published in the Environmental Research Papers, No. 427, AF CRL-72-0745, 29 Dec. 1972, "Atmospheric Transmittance from 0.25 to 28 micrometers: Computer Code LOWTRAN 2" and No. 331, AF CRL-70-0527, 22 Sept. 1970, "Optical Properties of the Atmosphere," by the Air Force Cambridge Research Laboratories.

The author wishes to express his appreciation to Capt. Neil D. McQuage for contributions regarding meteorological subjects.

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GLOSSARY OF SYMBOLS & TERMS

$R = \zeta_d$	Reflectivity (diffuse)
R_T	Target reflectivity
R_B	Background reflectivity
E	Spectral radiant incidence or irradiance
M	Spectral radiant exitance
L	Spectral radiant sterance or radiance
I	Spectral radiant intensity
I_0	Illuminator radiant intensity
τ	Atmospheric transmission
τ_1	Atmospheric transmission for target range
τ_2	Atmospheric transmission for the range of the scattering volume of atmospheric backscatter
L_{Si}	Spectral radiant sterance of atmospheric backscatter at distance (Si) below aircraft
L_T	Radiance of target
L_B	Radiance of background
L_{100}	Radiance for 100% reflectivity
h	Aircraft altitude
Z	Distance from ground to altitude at which gating takes effect
M_C	Inherent contrast modulation at the location of target and background.
M_{rec}	Contrast modulation at the focal plane of a sensor

GLOSSARY OF SYMBOLS & TERMS (CONT'D)

S_i	Distance from aircraft to the altitude at which gating takes effect
S	Distance from aircraft to the altitude for which stepwise integration is performed
γ	Atmospheric extinction coefficient per Km altitude
K_m	Molecular absorption
σ_m	Molecular scattering
K_a	Aerosol absorption
σ_a	Aerosol scattering
β'	Backscatter coefficient (per Km)

SECTION I

INTRODUCTION

In the development of active night photographic systems, backscatter imposes severe limitations, and the study of this problem has been pursued to improve night photographic systems for both low and high altitudes. The complexity and cost of a gated system to eliminate this problem is significantly higher than that of a nongated Photographic System. Therefore, we need to determine what benefits would be derived from using a gated active covert night Photo System. Specific situations were investigated in which the estimated target-background contrast or contrast modulation was compared for a nongated and a gated system. The effect of gating is described as a function of various parametric factors, including flight altitude, the atmospheric conditions for a given meteorological visibility as recorded in the records published by the Air Force Cambridge Research Laboratory, and the gated altitude or distance below the aircraft for which backscattered light is gated out. The objective of this study is to determine the degree of improvement a gated system would provide under environmental conditions frequently encountered.

The demand for technical support in other tasks limited the number of environmental variations we could use in making a quantitative determination of the target contrast modulation at the aperture of a photographic sensor. Two situations, an upper and a lower limit, have been derived for which the degree of gating and contrast modulation are determined.

In this report we will not provide any extensive explanations as to the general gating aspects. Instead we will present data on contrast reduction due to given atmospheric situations, and target background reflectance values which are frequently encountered on the basis of the accumulated data in the target background data base.

SECTION II

APPLIED TARGET/BACKGROUND SITUATIONS

In this section we will discuss and provide examples of the 2:1 contrast ratio value as a frequently occurring situation in the real world environment. During a data accumulation period we stored data on many targets and background reflectance characteristics in the target signature data bank. With this data, we have been able to establish, to a degree, a realistic statistical overview of the frequently occurring response characteristics of target surfaces and background surfaces in the wavelength regions from 0.3 to 15 micrometers. This data and other reports have been searched to relate this investigation to inherent contrast values which will frequently be encountered. Examples of 16 variations of such data are given in Figures 1 through 8. These are the result of a large number of observations.

The target-to-background contrast ratios can be expected to vary widely when many of the target background factors are varied. In Figures 1 through 8, the horizontal axis represents the contrast ratio of the mean reflectance of a target surface coating (or its basic material) to the ρ_d reflectance of the backgrounds in which it may be imbedded. The axis is divided into a positive part and a negative part indicating the inverse value. The vertical axis represents the statistical occurrence in a relative scale. At the scale value of 1.0, the ratio of the contrast occurrence is that target-to-background contrast resulting from the ratio of the ρ_d mean value of the target to that of the background material (dry soil, vegetation, asphalt, etc). At the 0.66 scale value of the vertical axis, the contrast ratios have been extracted from the 1σ background variations versus the referenced target reflectance.

This provides, to a degree, information on the spread of contrast variations with regard to various ground situations, and generally says that one should not base considerations on a specific number, but rather on some limited range of contrast situations. Any statistical

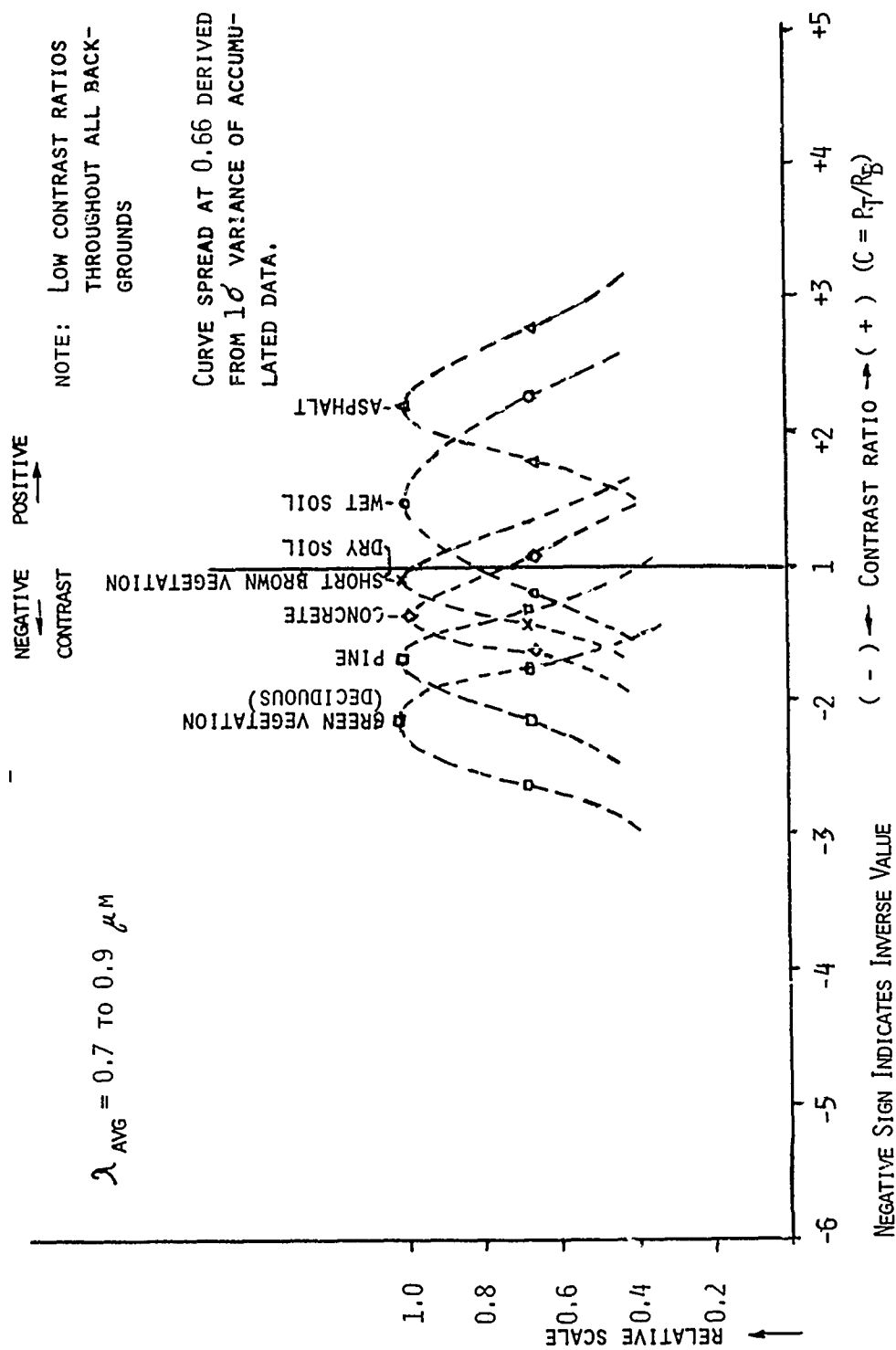


Figure 1. O.D. Canvas and Blue-Gray Tarpaulin, ρ Mean = 26% vs. Various Backgrounds

FOR $\lambda = 0.72$ TO $0.9 \mu m$

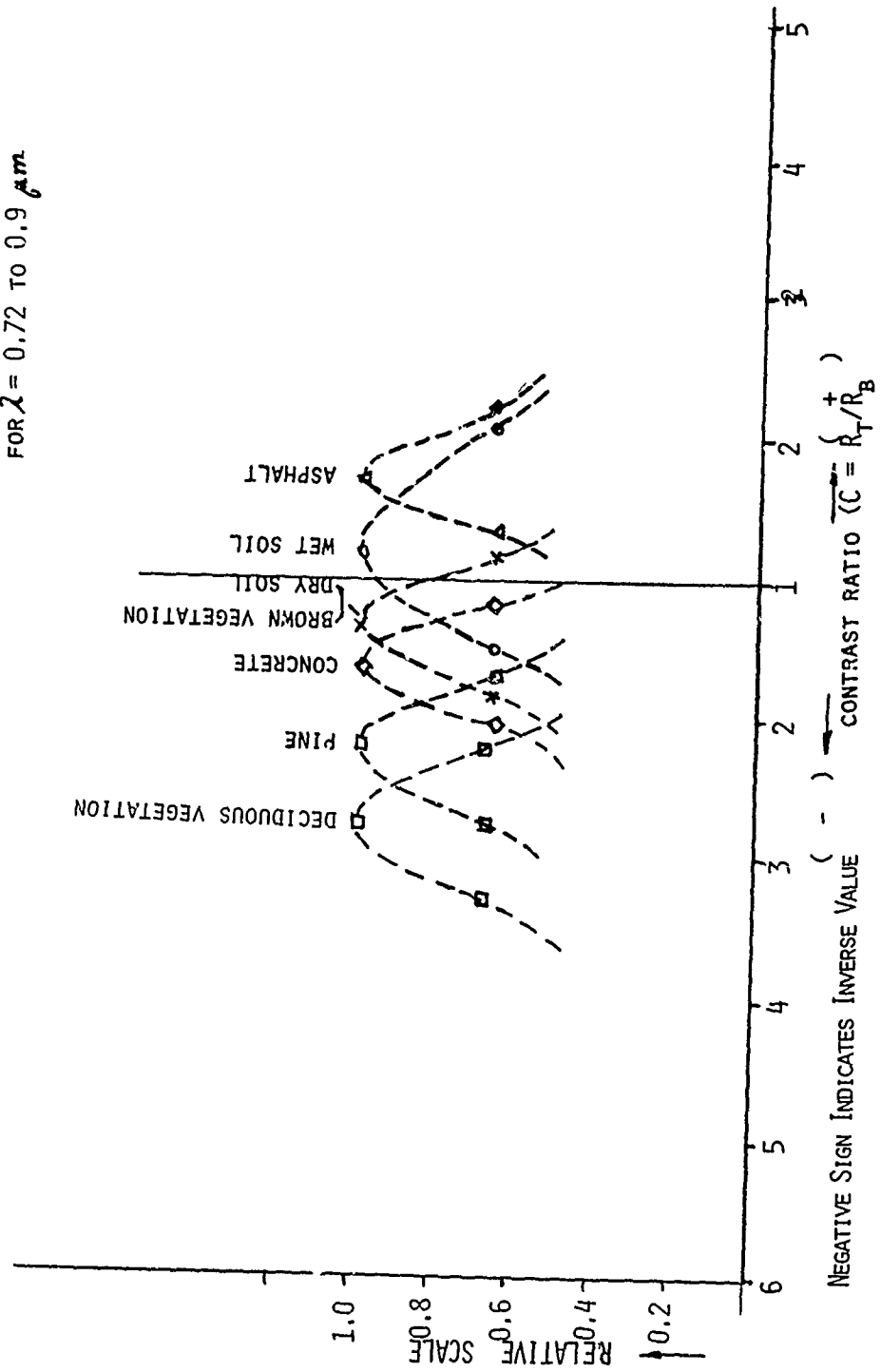


Figure 2. Mosquito Netting and Amphibious Vehicle, ρ Mean = 20% vs. Various Backgrounds

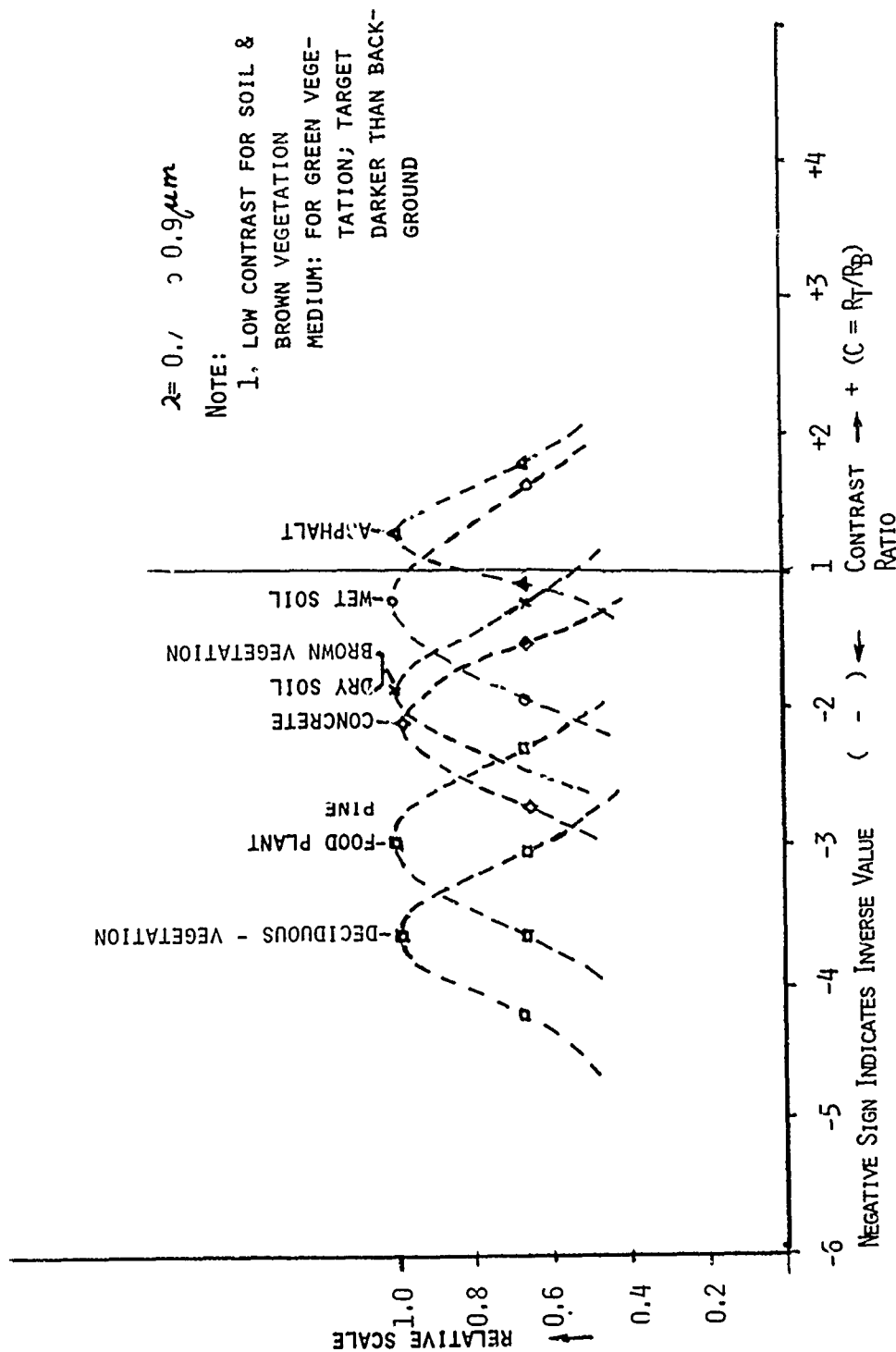


Figure 3. Aircraft Surface, ρ Mean = 15%, vs. Various Backgrounds

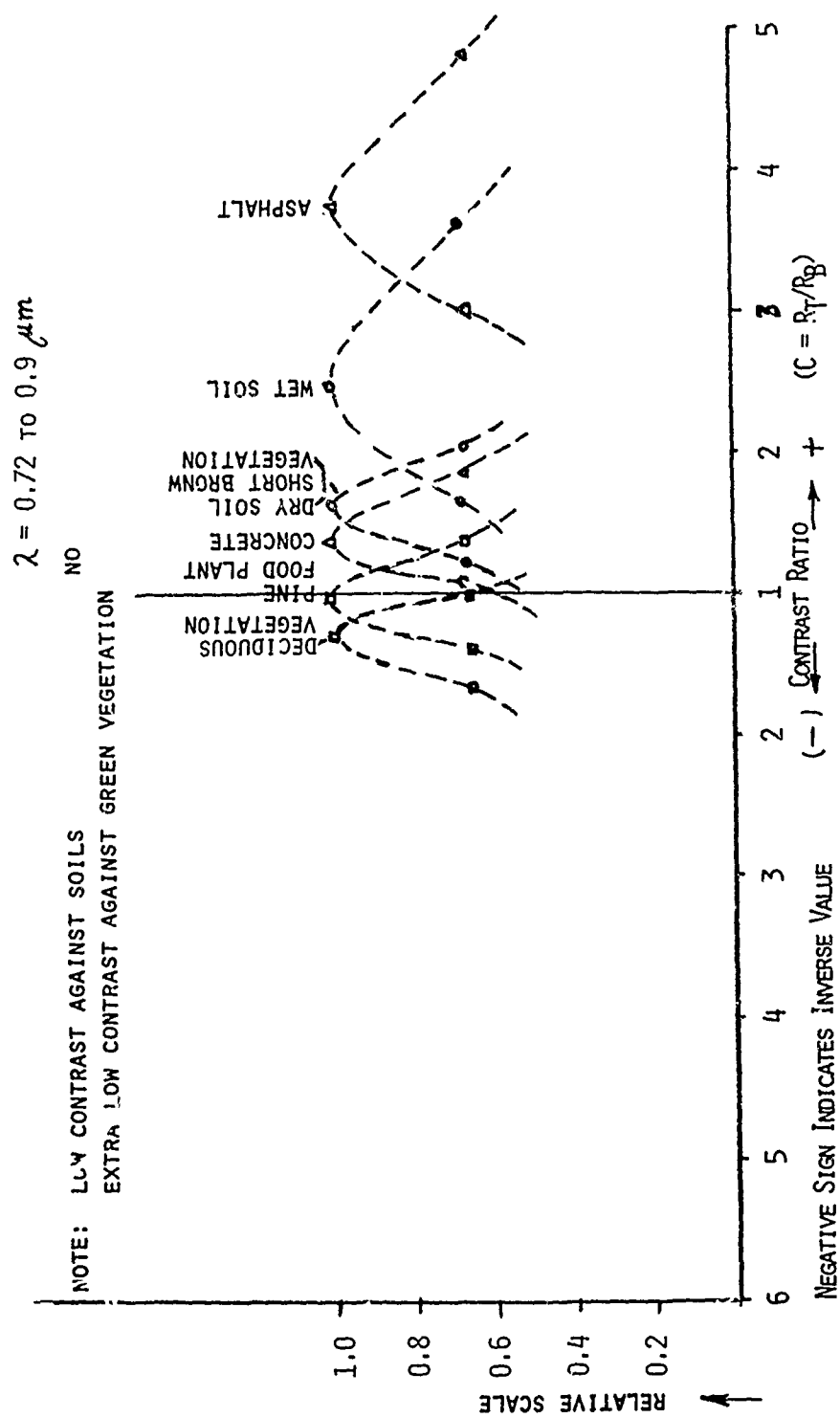


Figure 4. High Reflecting O.D. Burlap, Green Paints, and Field Drab Paints, ρ Mean = 45% vs. Various Backgrounds

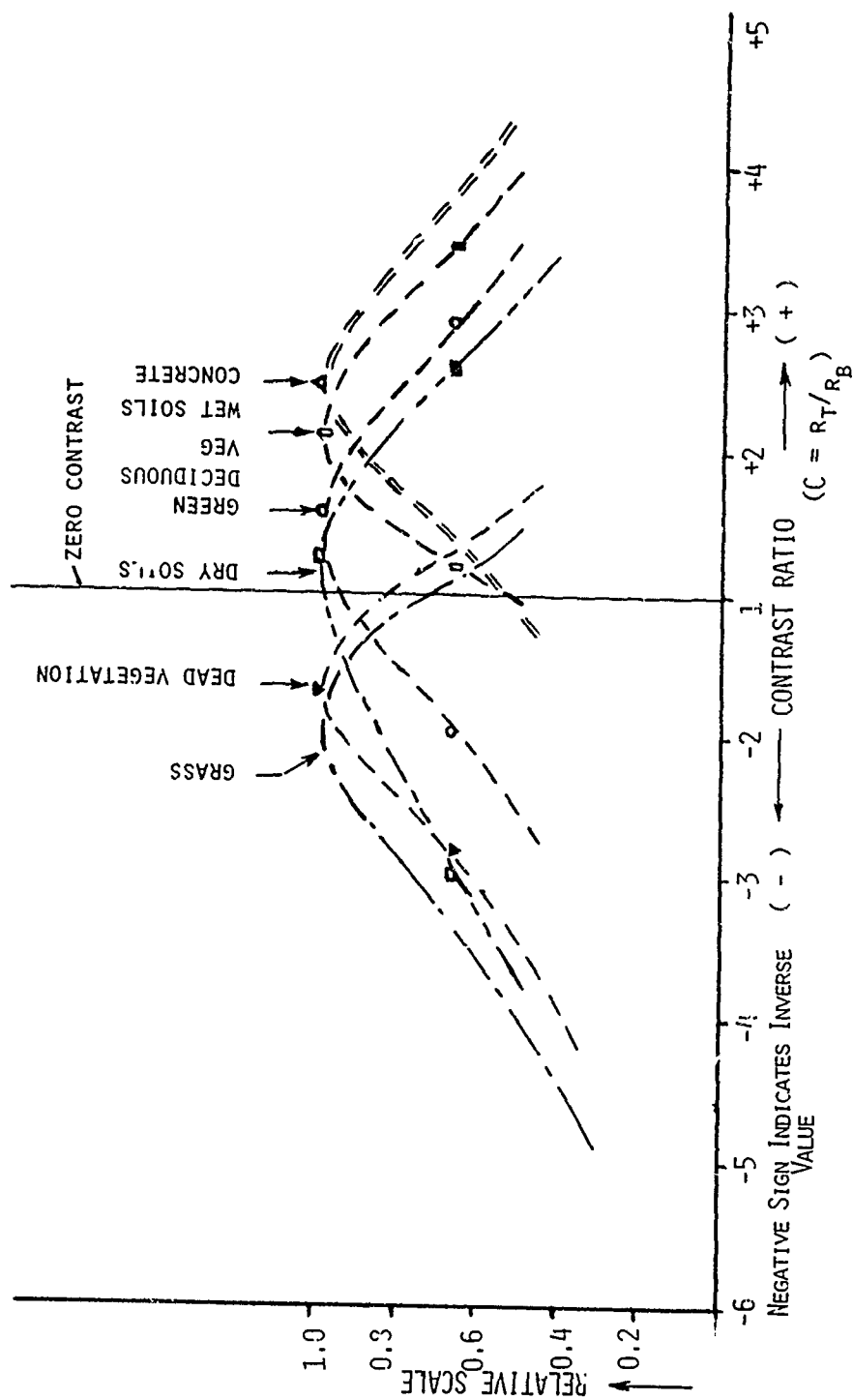


Figure 5. High Reflecting 0.0., Solar-Heat Reflecting, ρ Mean = 42% vs. Various Backgrounds

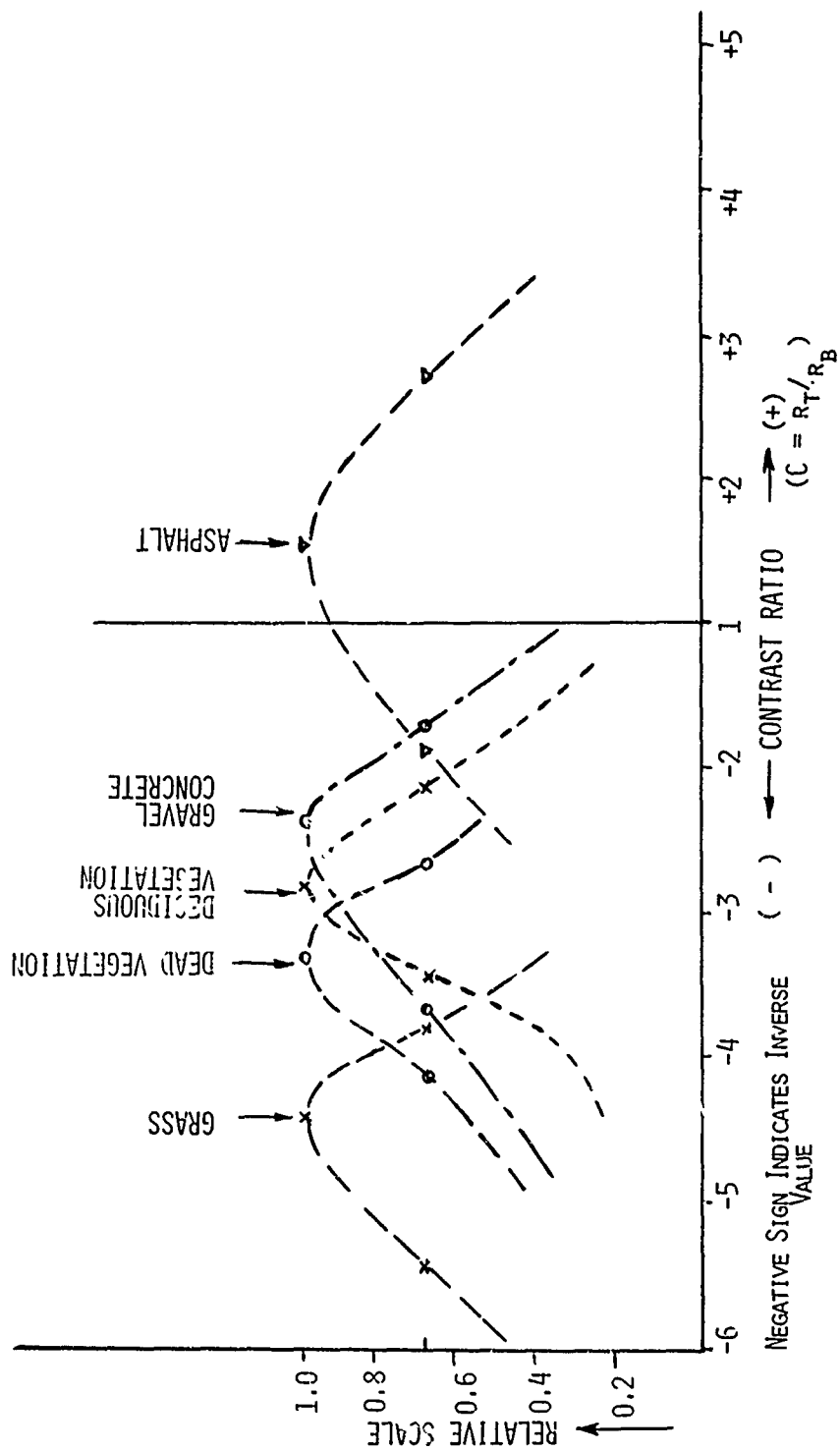


Figure 6. Medium Reflecting 0.D., ρ Mean = 12% to 15%, vs. Various Backgrounds

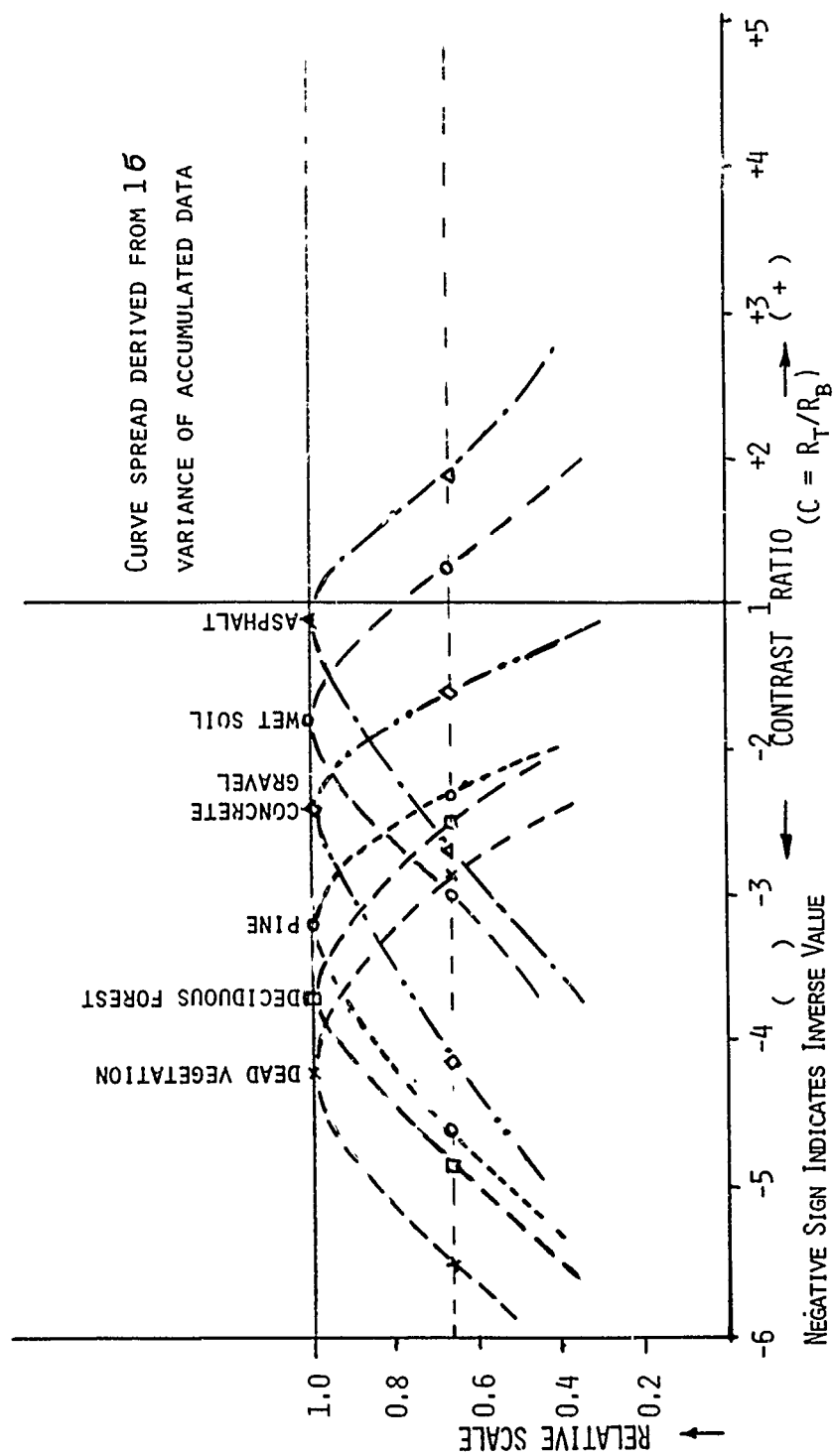


Figure 7. O.D. Canvas, ρ Mean = 15% vs. Various Backgrounds

$\lambda = 0.72$ TO $0.9 \mu m$

NOTE: STRONG NEGATIVE CONTRAST
FOR ALL EXTRA LOW REFLECTING
OBJECTS;

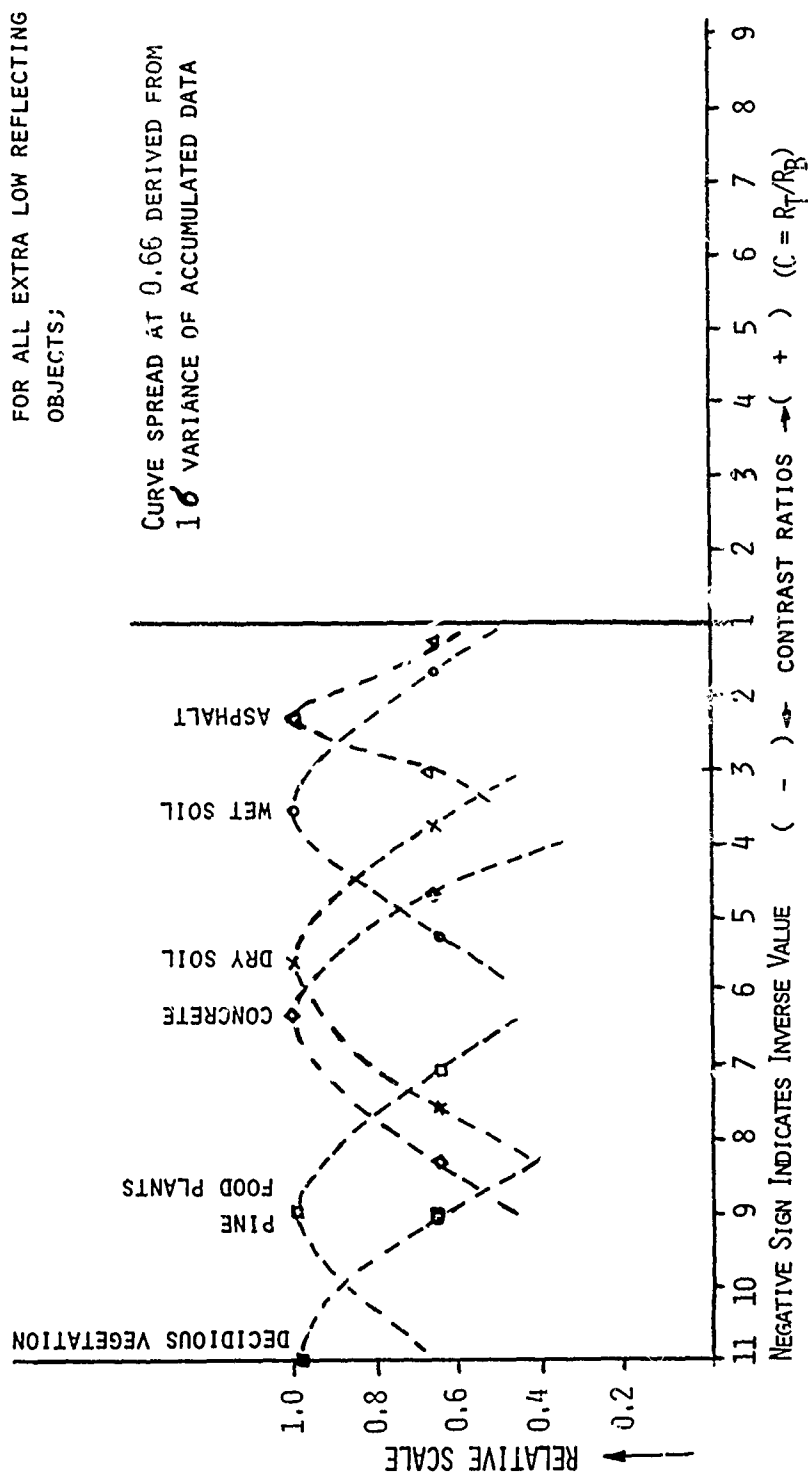


Figure 8. O.D. Points of Extremely Low Reflectance, ρ Mean = 5%,
vs. Various Backgrounds

accumulation is limited, to a degree, with regard to the number of samples obtained and to the environmental conditions included in the sample combinations.

High contrast targets are shown, but the surface treatment of many military targets is such that their appearance is either relatively close to the environment or their reflectances are so low that the detection of the equipment is minimal. For example, the O. D. Canvas with a reflectance $\zeta_d = 26\%$ (Figure 1) and the mosquito netting with a $\zeta_d = 20\%$ (Figure 2) show contrast values of 2:1 and less against background materials such as pine forests, dry and wet soil, brown vegetation, and asphalt. The frequency of occurrence of contrast ratios of 2:1 and less, for both positive and negative contrast, requires that reconnaissance aircraft have sensors capable of detecting targets with an inherent contrast of 2:1 and less.

Based on this consideration, the 2:1 contrast ratio is used as the reference value for the investigation of the received signal contrast ratio at the sensor aperture where nongated and gated systems capabilities are compared. Higher contrast values of 3:1 do occur, of course, but low contrast conditions do exist frequently. Apparent target contrast values as received at the entrance aperture of a sensor for a given flight altitude, therefore, should be established at a threshold value for an inherent contrast on the ground of 2:1 or less. If the contrast is reduced by the backscatter and other atmospheric effects such that the apparent contrast at the sensor aperture is below a detectable threshold, then the photographic quality will not be adequate for detecting these targets, and, in general, would not meet military requirements beyond certain altitudes.

Curves have been derived which display the apparent contrast modulation at the entrance to the sensor aperture for each flight altitude with various degrees of gating from a nongated to the fully gated condition (when only the light reflected from the scene is received).

Graphs are included which display the directional reflectance ζ_d of various materials and backgrounds as a function of the spectral wavelength region between 0.69 and 0.9 μm . This spectral region is applied in context with the spectral zone applied by the illumination sources and their filterbands used with an image intensifier. Filters with a cut-on wavelength of 0.72 or possibly 0.7 μm are used for covert illumination.

Figures 9 through 15 display mean reflectance values (ζ_d mean) and the 1σ variation of a number of target surface coatings and background materials which have been applied for a determination of statistical information on contrast ratios. These are examples of a wide variety of response characteristics accumulated in the Target Signature Data and Analysis Center (TSAC). This source may be consulted for the retrieval of other information and related literature and data in different spectral regions or boundaries.

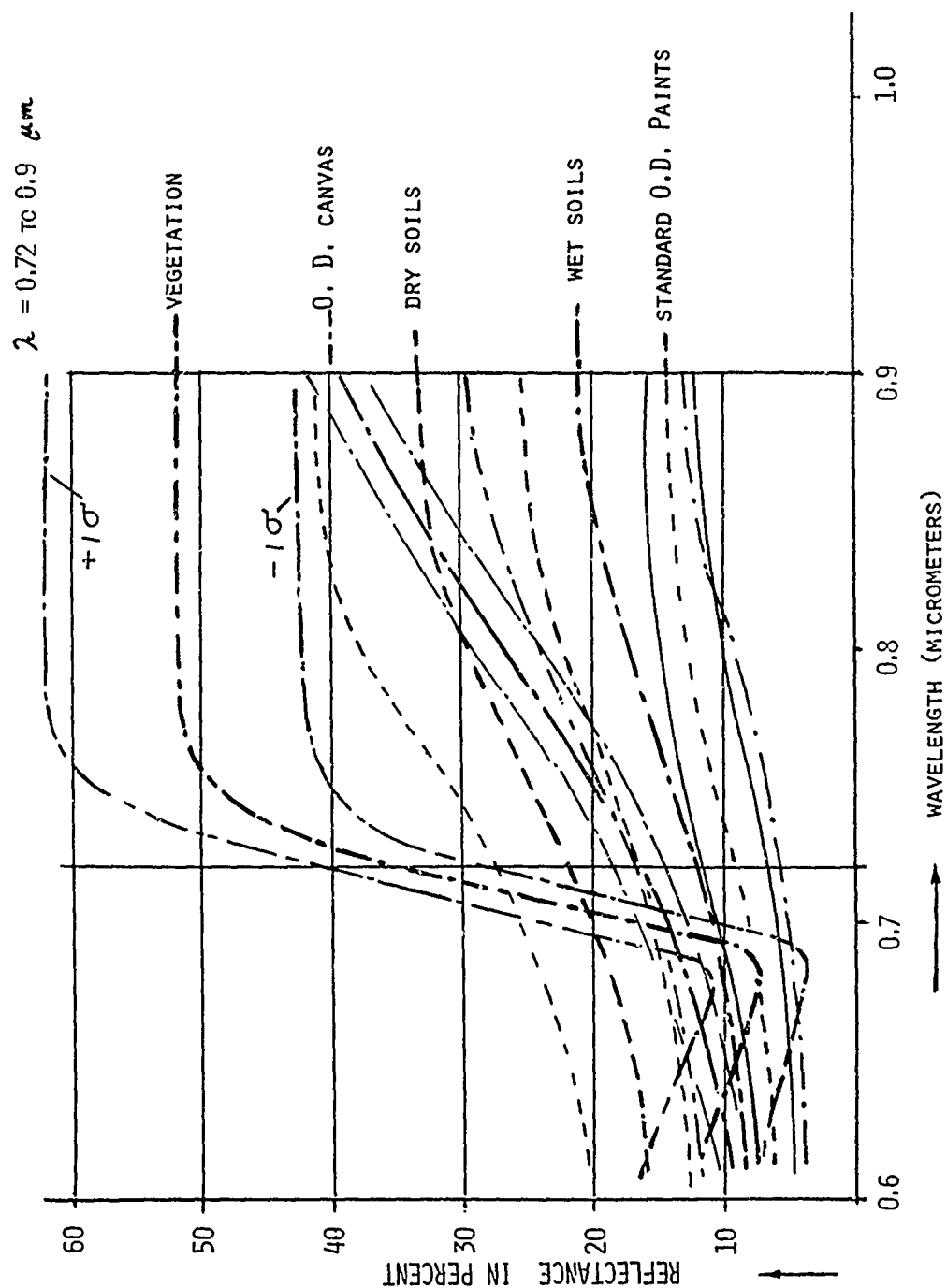


Figure 9. Medium Reflecting 0.D. Compared With Various Backgrounds

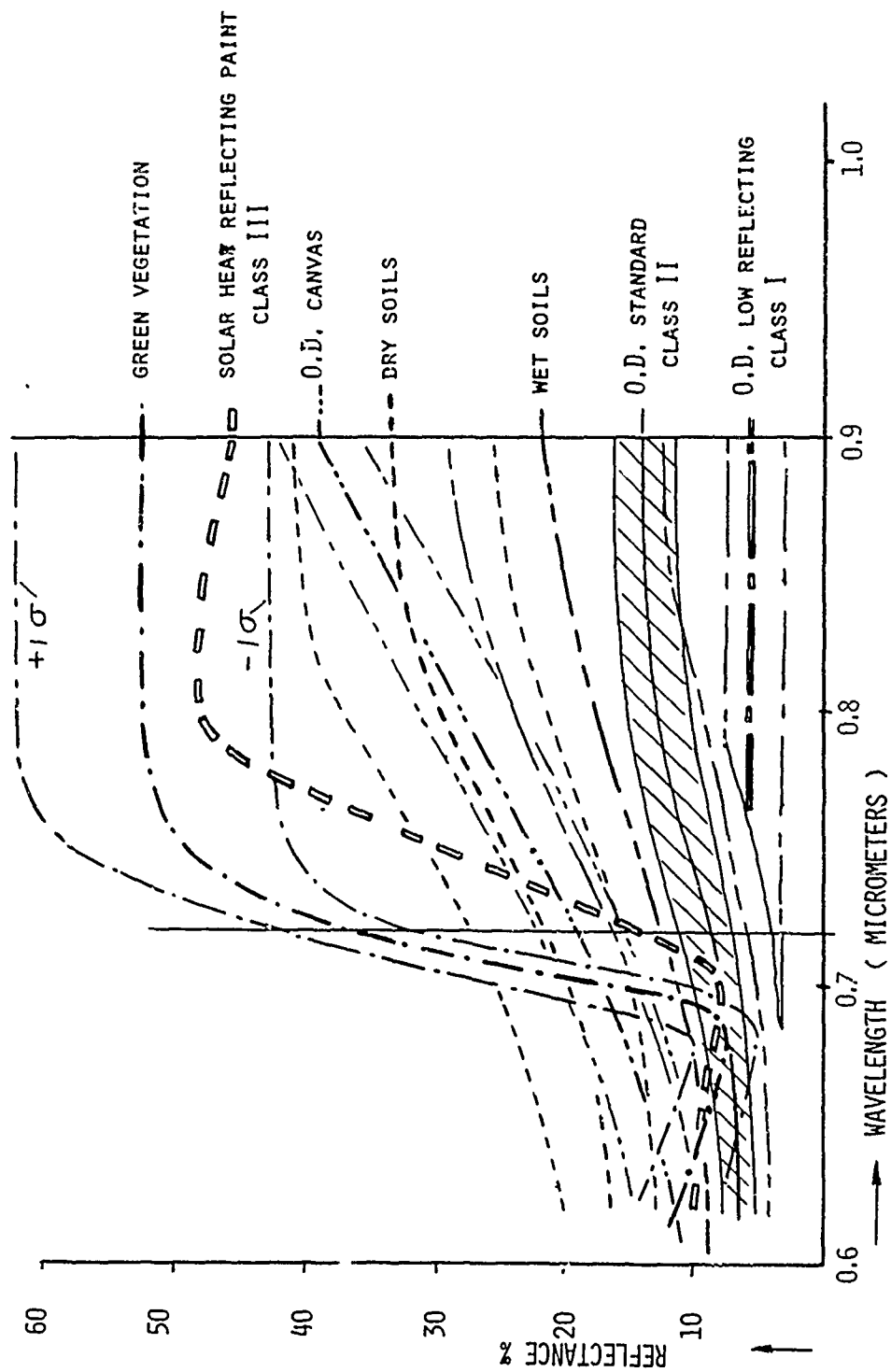


Figure 10. Several Types of O.D. Paints Compared With Various Backgrounds.

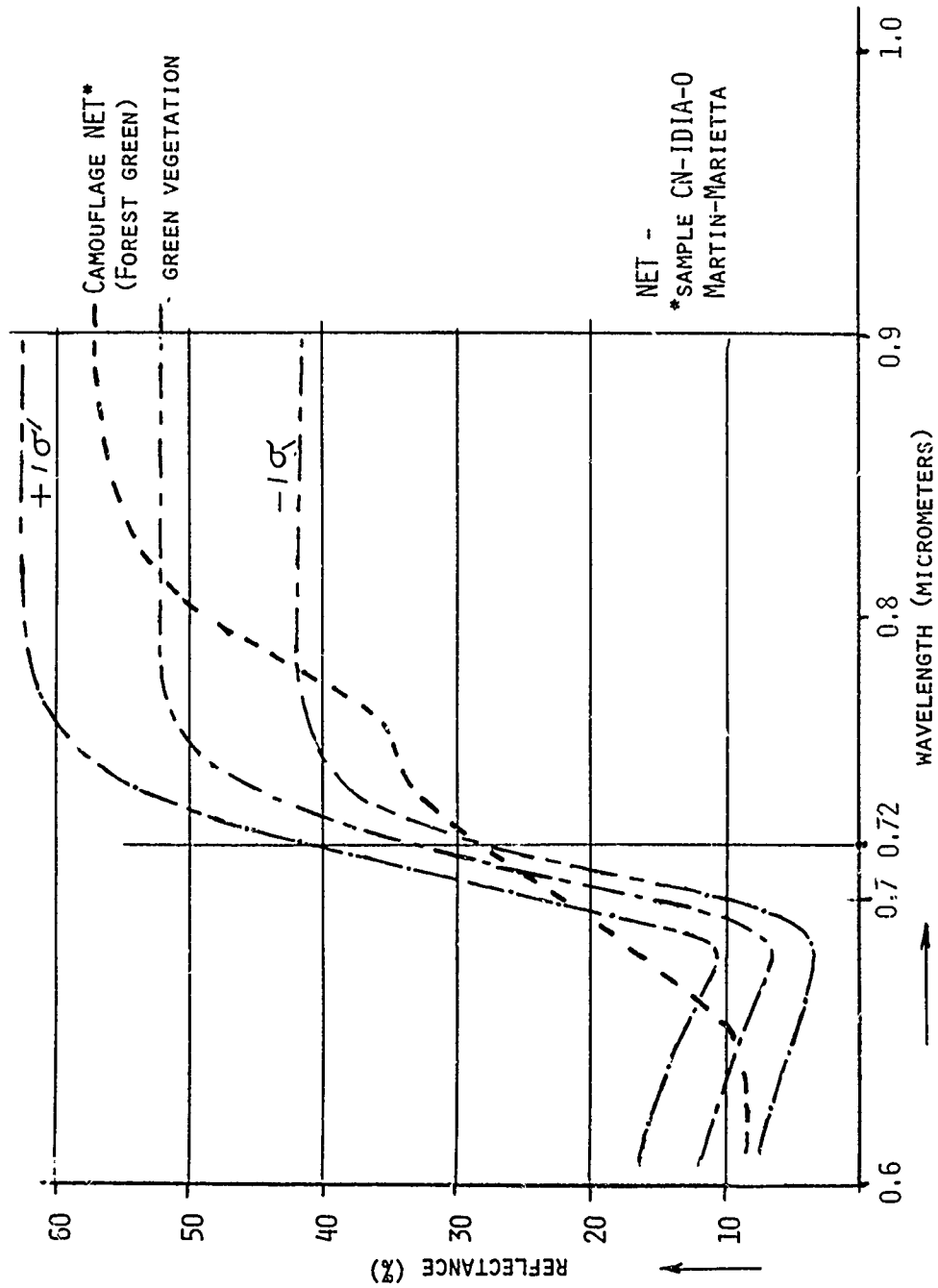


Figure 11. Camouflage Net Compared With Vegetation

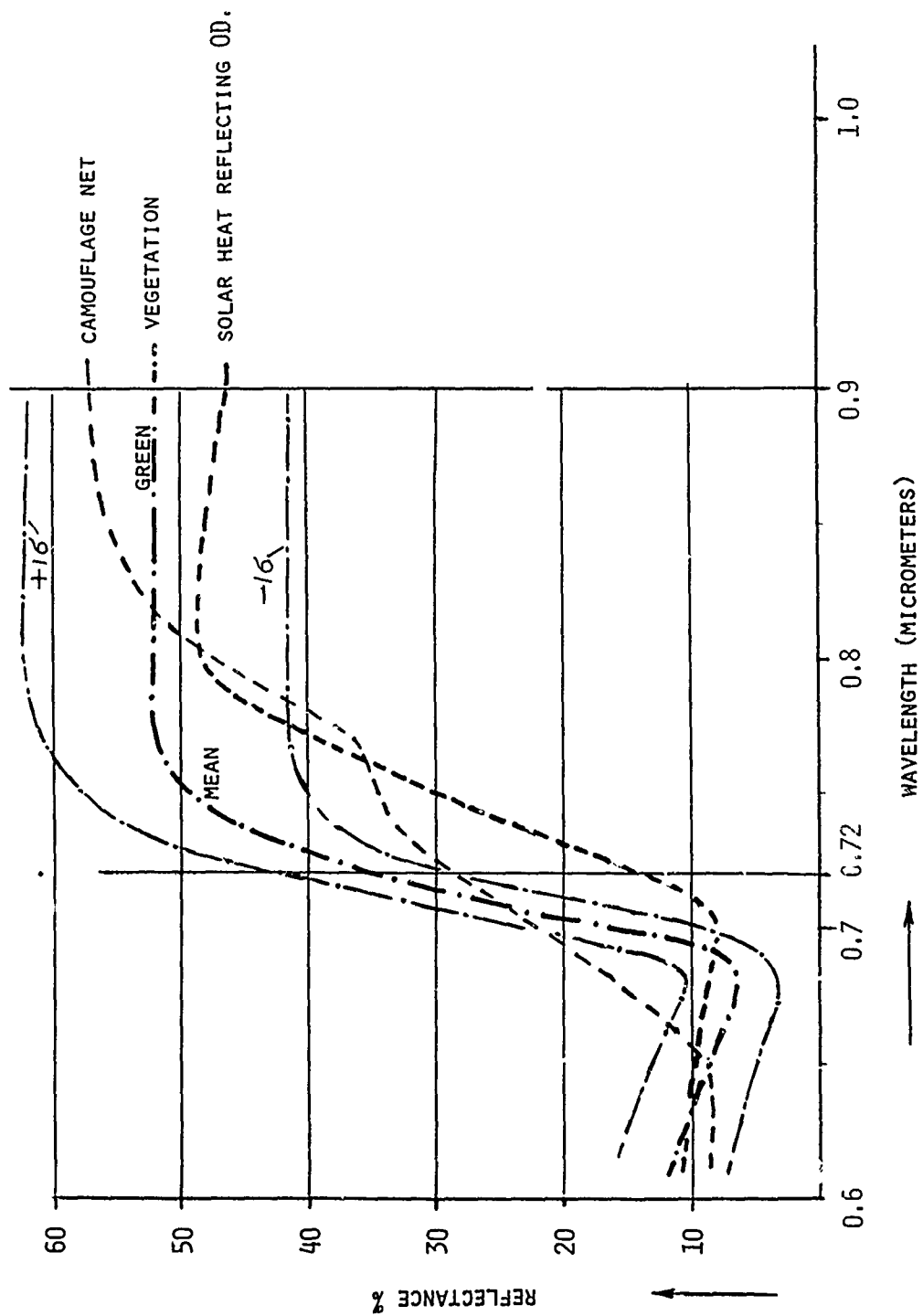
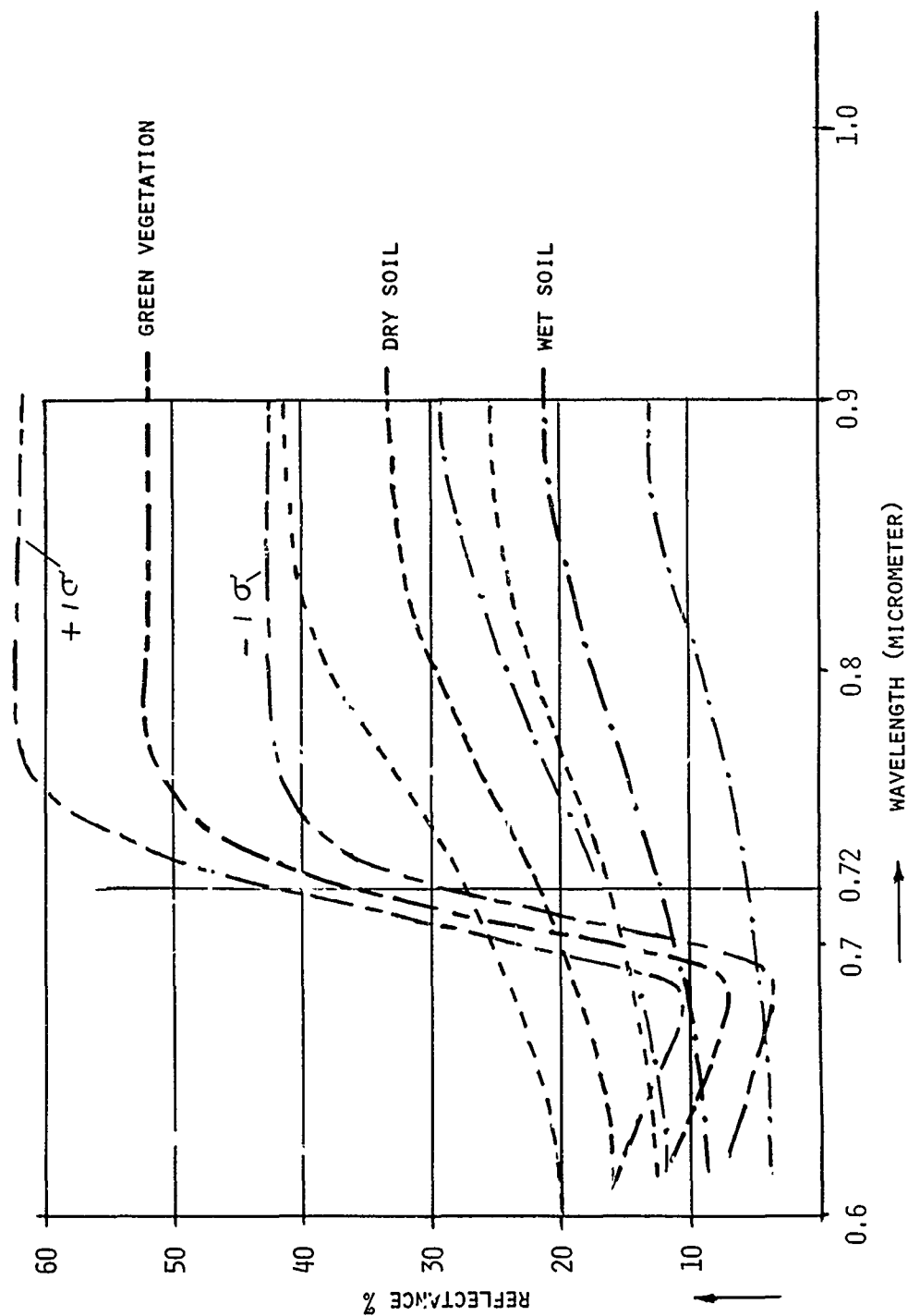


Figure 12. Solar Heat Reflecting O.D. and Camouflage Net Compared with Foliage

Figure 13. Natural Backgrounds, Average Value and $\pm 1\sigma$ Variation

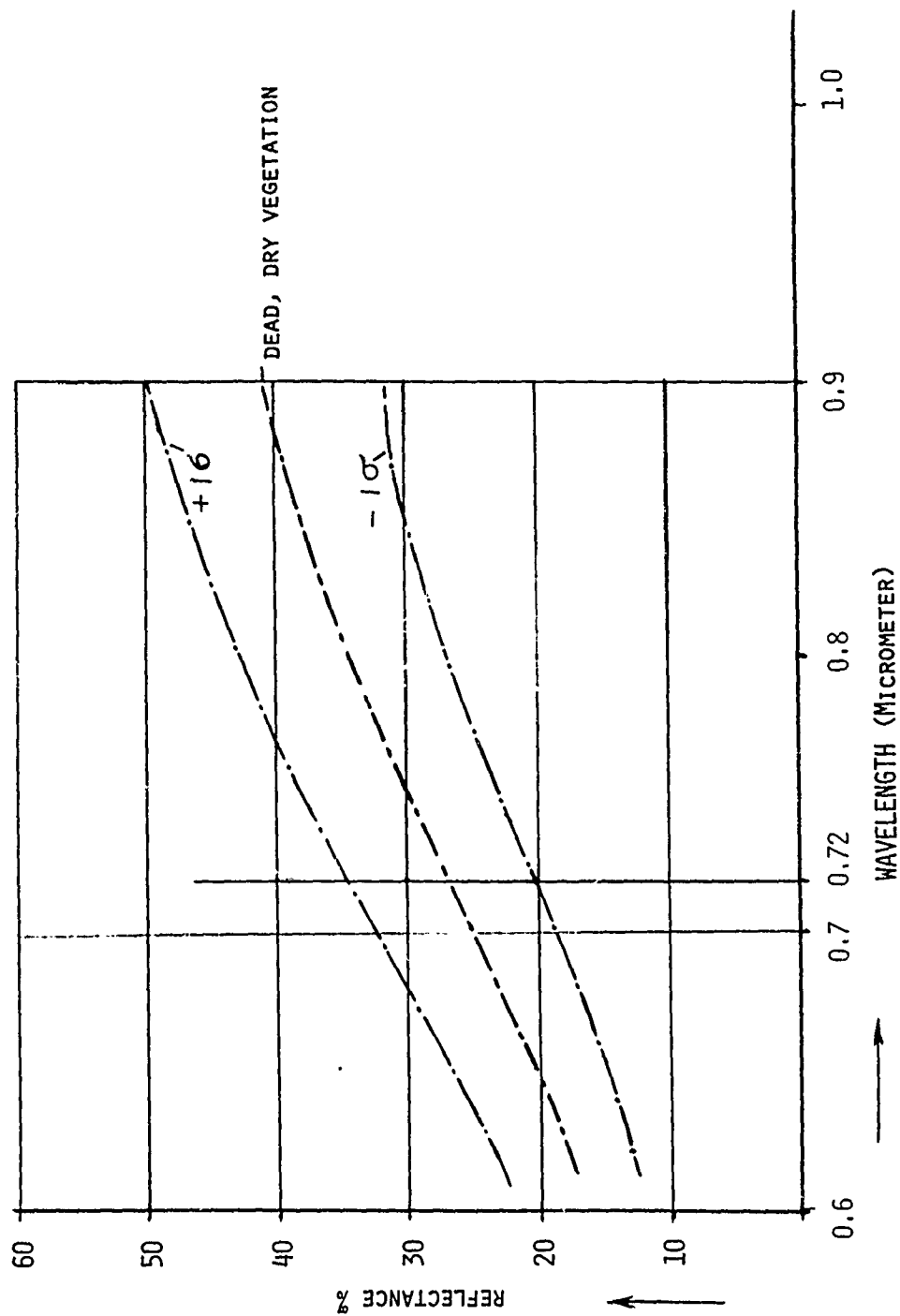
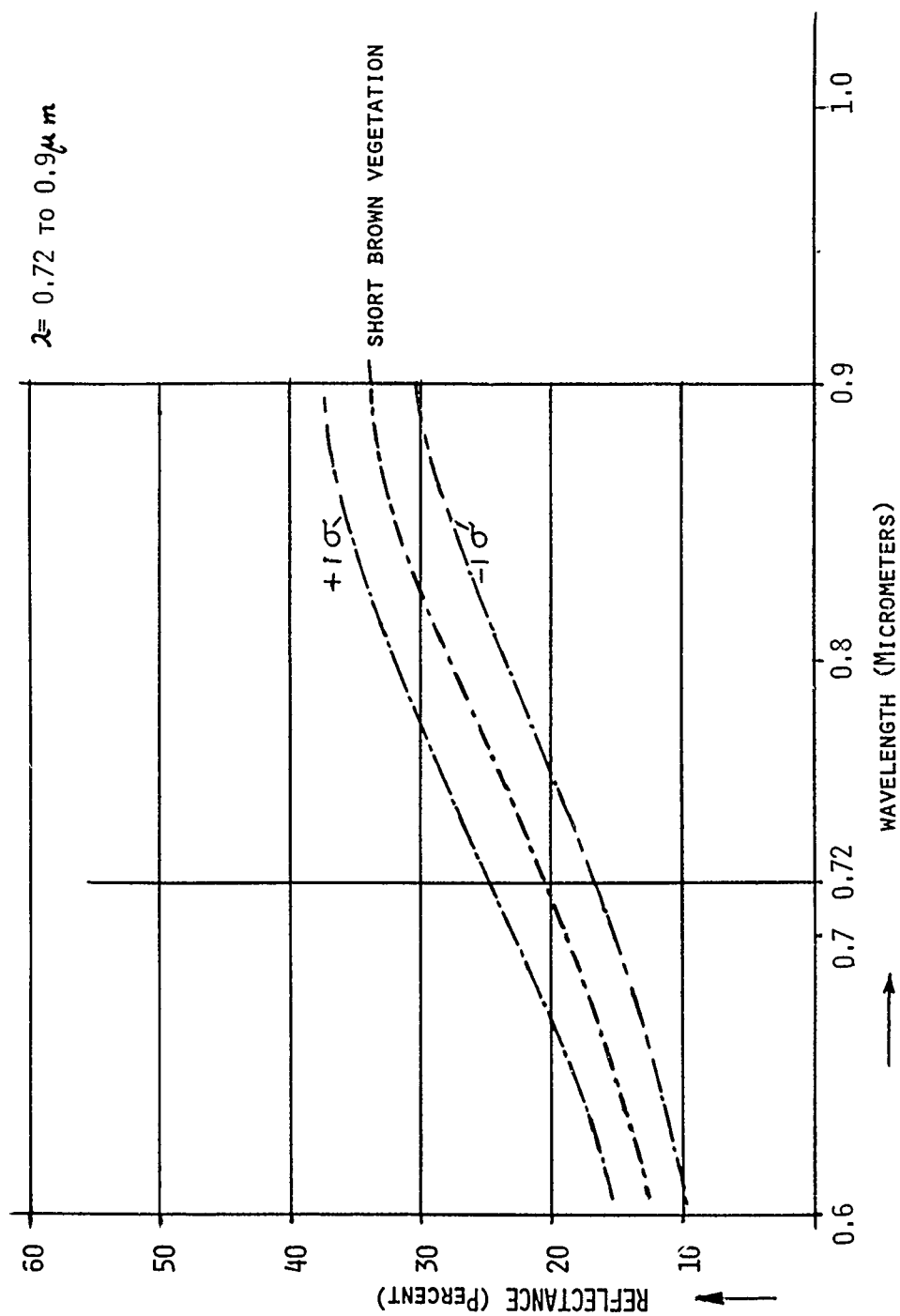


Figure 14. Brown Vegetation From Various Sources, Average Value and $\pm 1\sigma$ Variation

Figure 15. Short Brown Vegetation, Average Value and $\pm 1\sigma$ Variation

SECTION III

CONTRAST MODULATION AS A FUNCTION OF THE GATED
ALTITUDES BELOW AIRCRAFT

The effects of gating in regard to backscatter for a single source illumination is investigated for two borderline cases of atmospheric conditions. The respective atmospheric constants have been taken from the data published by the Air Force Cambridge Research Laboratory (Reference 4). Two situations have been related as borderline cases which include a large number of frequently occurring situations: (1) a hazy atmosphere with a nominal meteorological visibility of 5 Km, and (2) a clear atmosphere with a ground visibility of approximately 23 Km. Weather conditions with meteorological ranges between these limits will require gating altitudes below the aircraft between the performance curves presented here.

The extinction coefficient (γ^T per Km) versus altitude and the backscatter coefficient (σ per foot) versus altitude have been extracted from Reference 4 and are presented in Figures 16 and 17.

In general, the influence of gating is strongest for atmospheric regions below and relatively close to the aircraft. This is verified in the derived curves by the fact that the change of the contrast modulation is the steepest at short distances below the aircraft as a function of gated distances from the light source.

For these two atmospheric conditions, the target contrast modulation is displayed for gated distances starting from ground level up to close to the aircraft. Ideally, if the gating would eliminate all atmospheric backscatter between the aircraft and ground, the inherent contrast modulation at ground level would essentially be transmitted to the sensor even though the signal strength may be drastically reduced by absorption, depending on the transmission factors.

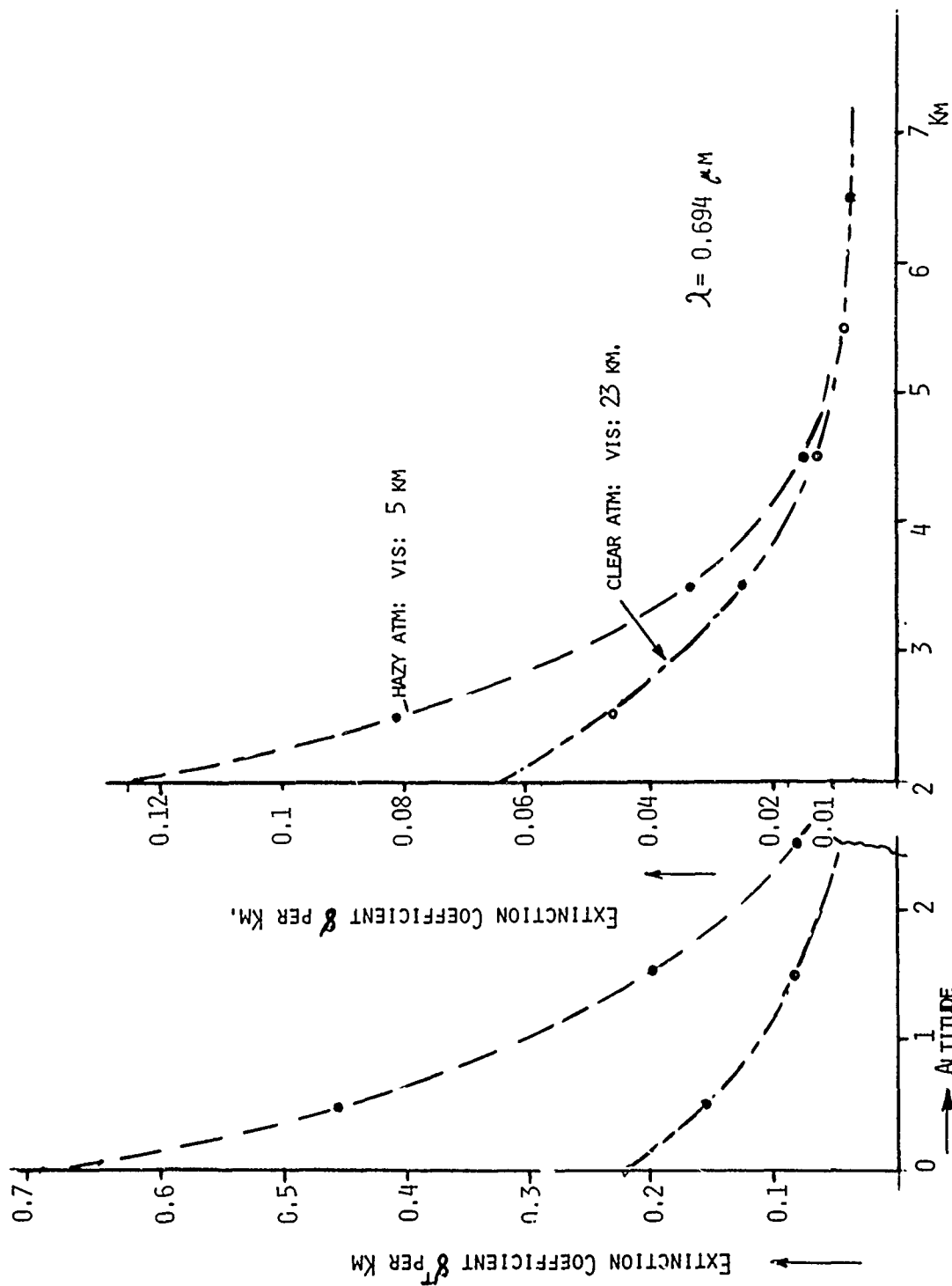


Figure 16. Extinction Coefficient γ^T per KM
(From Reference 4)

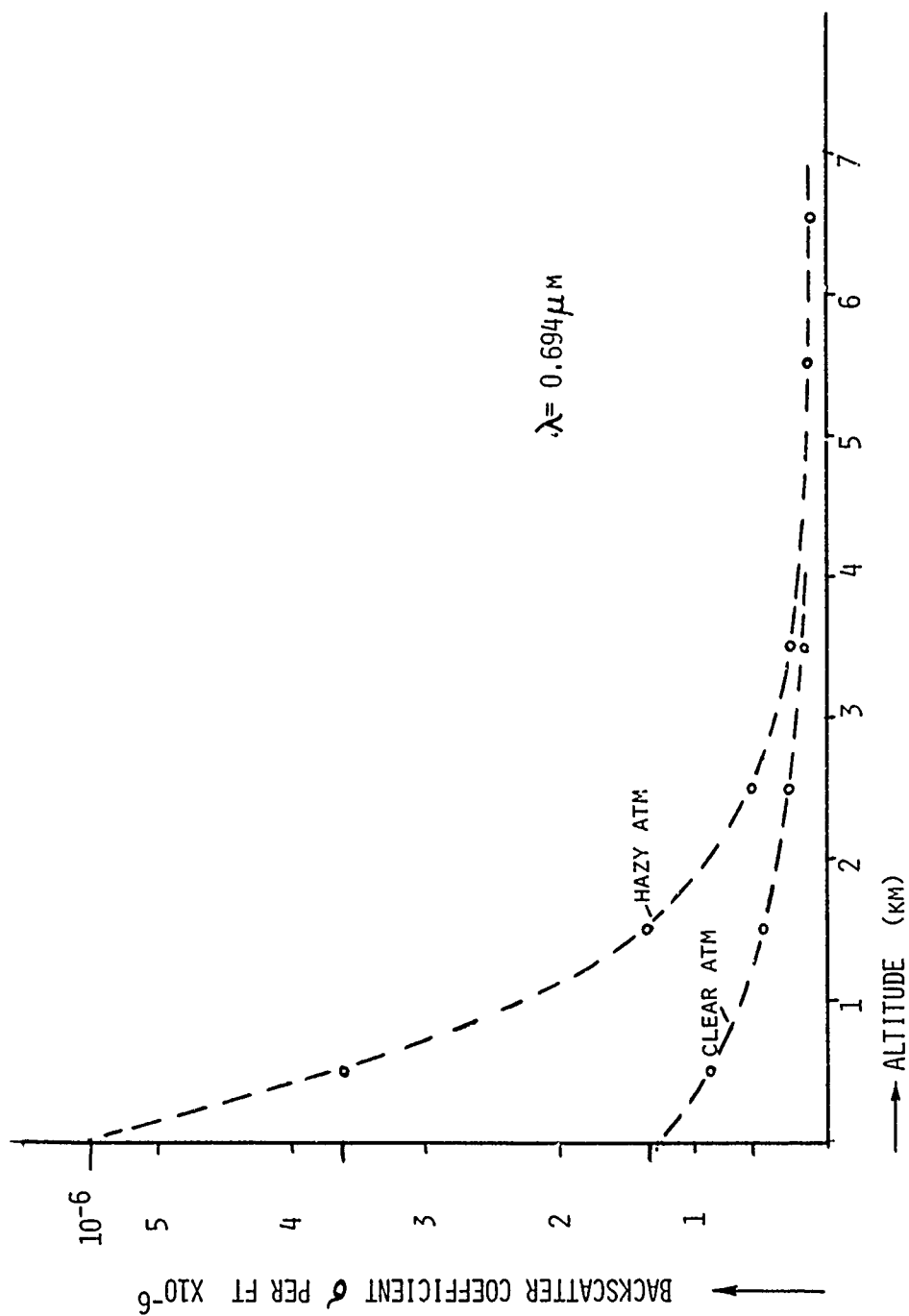


Figure 17. Backscatter Coefficient " σ " per Foot vs. Altitude
(From Reference 4)

The contrast modulation for gated distances starting from the ground level and progressing through all altitude levels up to a short distance below the aircraft, has been evaluated for a number of flight altitudes. Figures 18 through 20 present data representing altitudes of 2,000, 6,000, 9,000, 16,500, and 23,000 feet.

Some amount of gating up to a certain distance below the aircraft is essential for almost all altitudes except low altitudes (e.g., 2,000 feet or somewhat higher) where the reflected intensities from the targets are high and the absorption is sufficiently low that the backscattered intensity does not completely deteriorate the contrast. At low altitudes, the separation between the sensor and the illuminating source serves as a gating equivalent in maintaining contrast modulation to a sufficiently high degree; e.g., for a limited field-of-view of 20 degrees, a 15-foot separation of sensor and source will be equivalent to approximately a 100-foot gating distance.

The following is a discussion of characteristic reduction in the contrast modulation for aircraft flight altitudes of 5 Km (approximately 16,500 feet). A representative display is given in Figure 19. The influence of the gating as a function of altitude is shown in two scales. The scale to the left represents the change in contrast modulation as a function of the gated altitudes, starting at ground level (100% gated) up to the aircraft altitude, where no gating exists. Separation of the transmitter and receiver (e.g., 15 feet), to a limited degree, has the same effect as gating for a relatively short distance from the aircraft. The scale to the right represents the effect of gating at relatively short distances from the aircraft. The enlarged scale shows the minimum gated distance below the aircraft required to receive a contrast modulation $M_{rec} \geq .04$ at the sensor aperture if the inherent contrast at the target scene is $C_0 = 2/1$ or a contrast modulation $M_0 = 0.33$. The horizontal axis of these figures represents the contrast modulation $M_{rec} =$

$\frac{I_T - I_B}{I_T + I_B}$ received by a sensor for the gated altitude represented on the

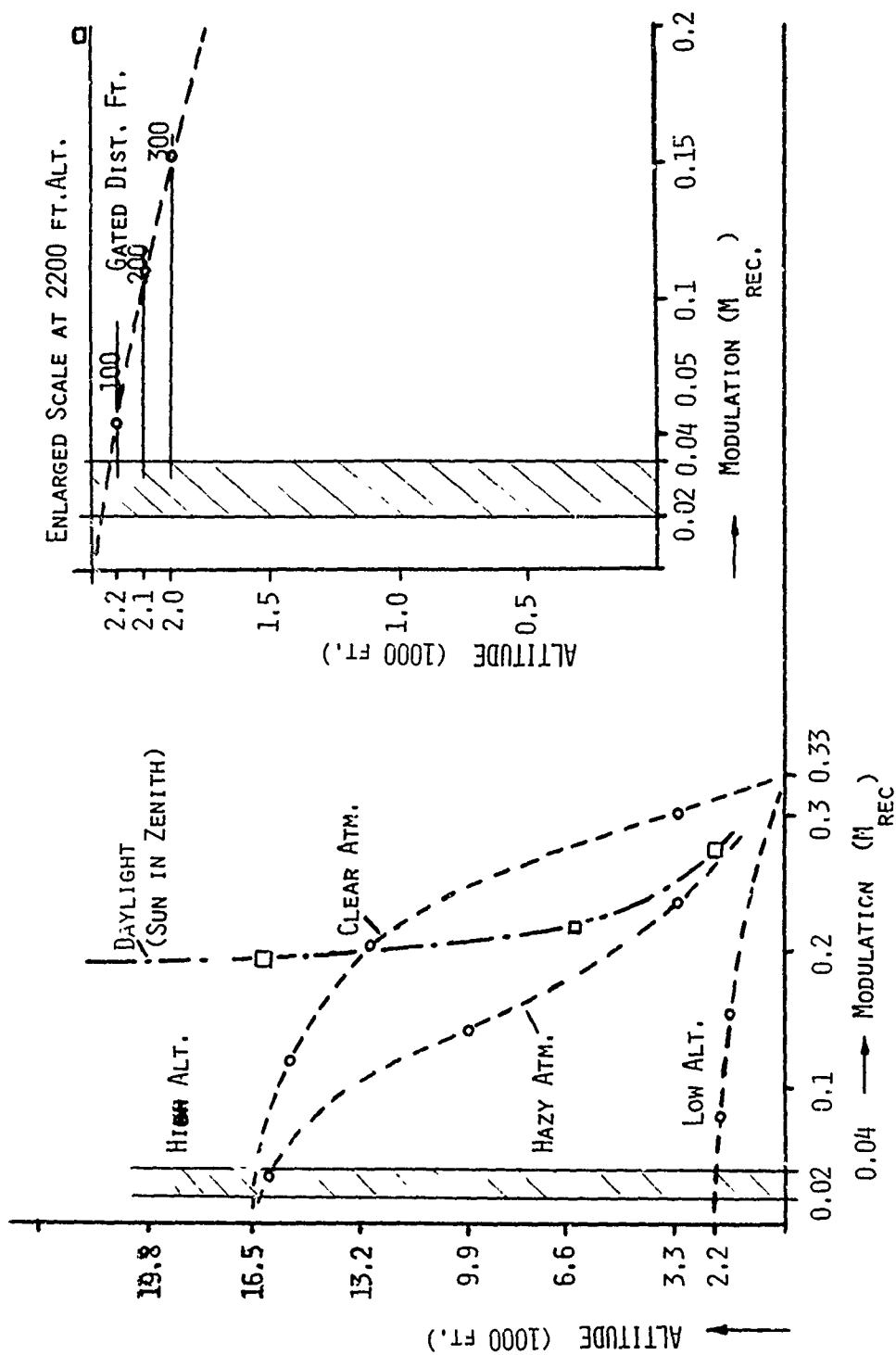


Figure 18. Contrast Modulation and Range Gating Enlarged Scale at 2.2 Thousand Feet

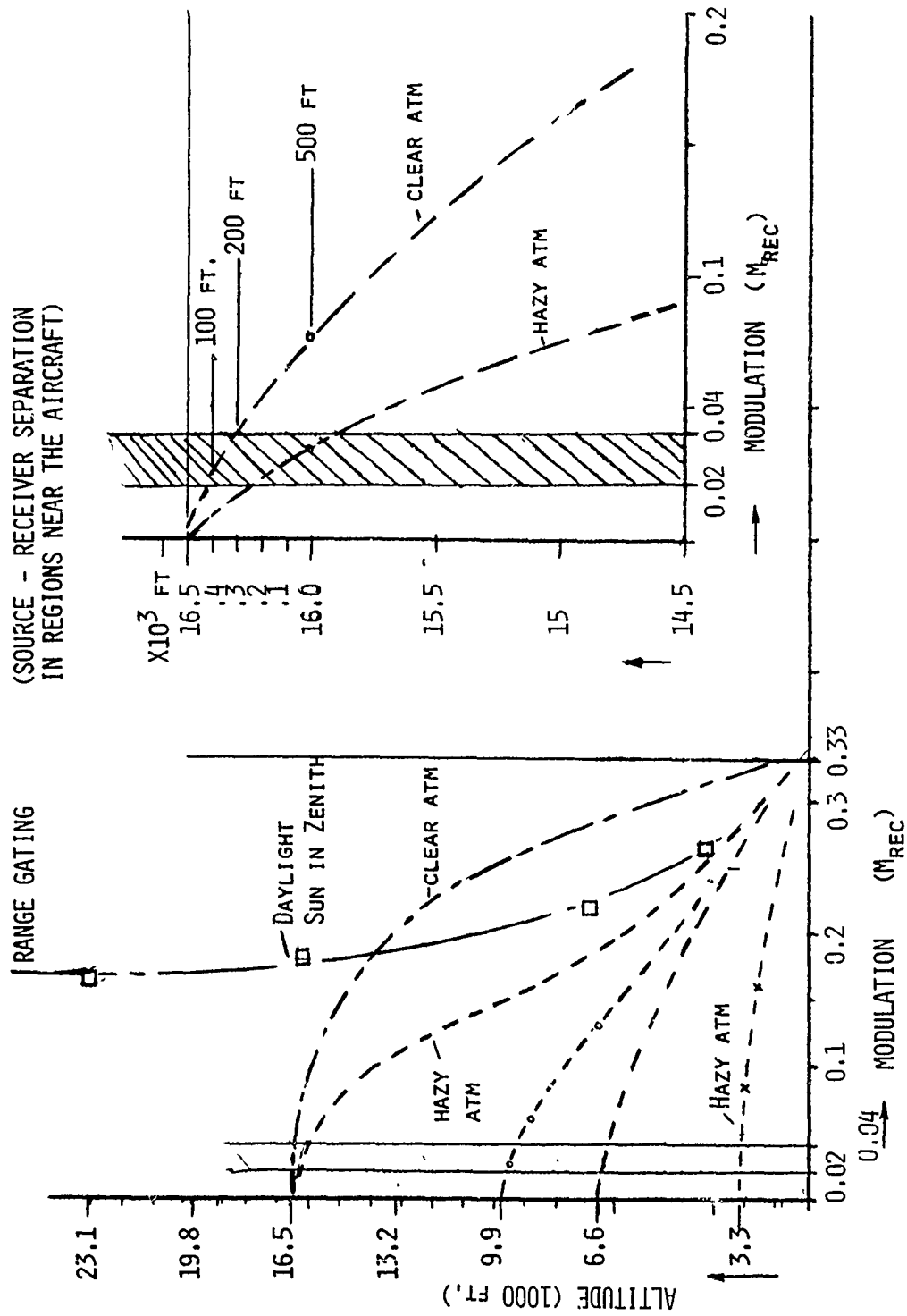


Figure 19. Contrast Modulation and Range Gating Enlarged Scale at 6.5 Thousand Feet

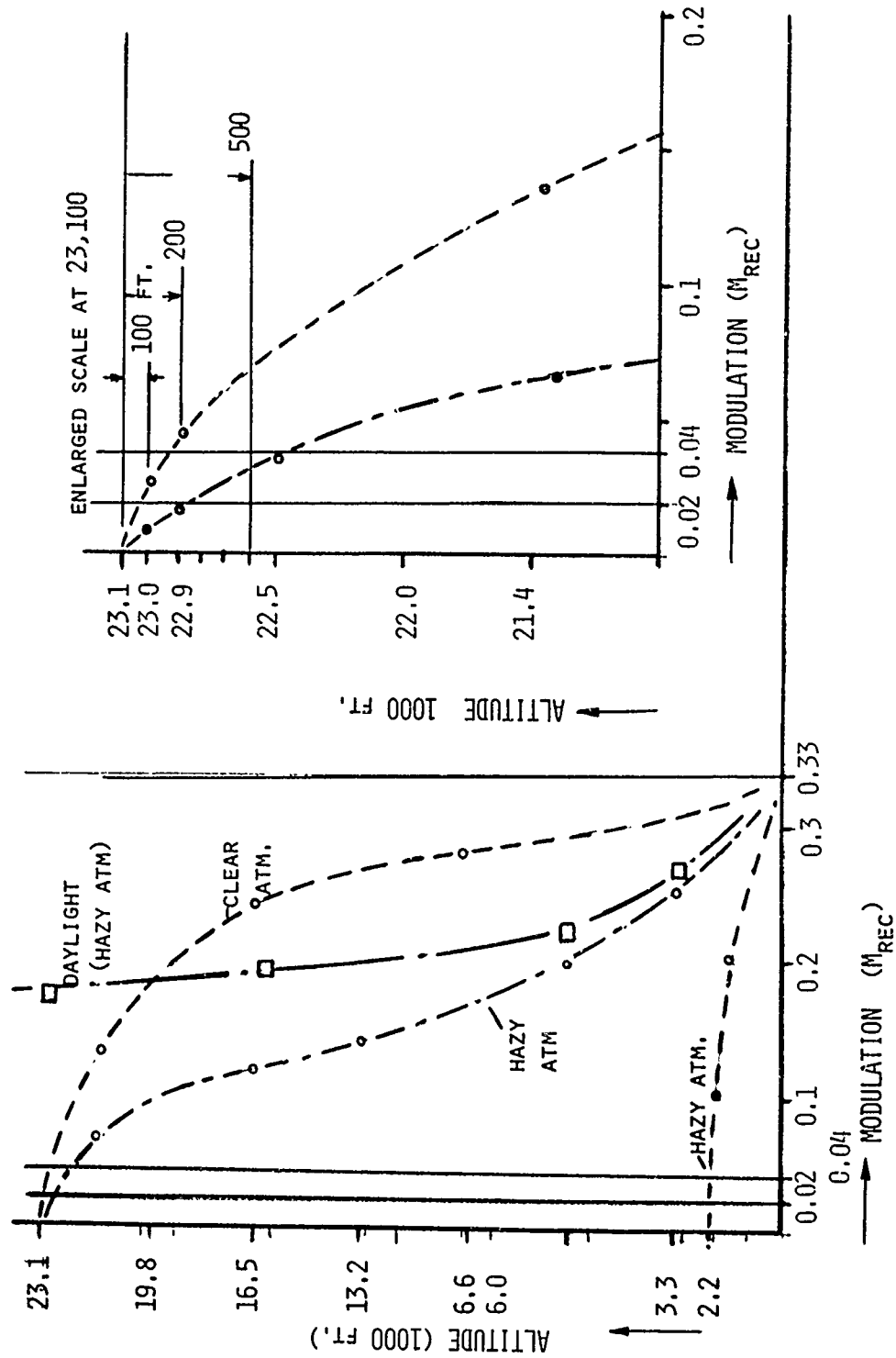


Figure 20. Contrast Modulation and Range Gating Enlarged Scale at 23.1 Thousand Feet

vertical axis ordinate. The shape of these curves clearly indicates that the strongest change in modulation occurs in two altitude regions: (1) at gated altitudes within the first several thousand feet from the ground, the contrast modulation decreases rapidly if the gated altitude increases; at altitudes halfway between ground level and aircraft flight altitudes, the contrast modulation decreases, but at a lower rate; and (2) at gated distances relatively close to the aircraft (100 to several thousand feet), the modulation decreases very rapidly. The two cases presented in Figure 19, as well as those for other flight altitudes (Figures 18 and 20), are derived for two atmospheric situations. The upper curve is valid for a relatively clear atmosphere with a meteorological visibility of 23 Km and the lower curve represents the results obtained for a hazy atmosphere with 5 Km visibility. Thus, the display represents the upper and lower boundaries for a wide variation of atmospheric conditions. Localized layers or regions of atmospheric haze are often encountered near the ground or at relatively low altitudes, and this has not been included in the study. Atmospheric variables regarding molecular scattering and absorption were obtained from tables of the Cambridge Research Laboratory (AFCRL) for average conditions resulting from previous research efforts. For hazy atmospheric situations, the scattering and absorption data are subject to strong changes at each kilometer up to altitudes of 4 Km. At higher altitudes, the rate of change gradually decreases. The curves for clear and hazy atmospheres in Figure 19 represent, to a degree, the upper and lower boundaries. Conditions between these limits will occur frequently.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

1. An analysis of target-background contrast showed that a contrast of 2:1 or less should be a prime consideration for many statistical targets. A reconnaissance system (photographic or otherwise) must be capable of discriminating targets with this low inherent contrast at the required flight altitudes.
2. Even in a relatively clear air environment, the inherent contrast of 2:1 (contrast modulation $M_o = 0.33$) may be reduced to a received contrast modulation of less than 1.1:1 or $M_{rec} = 0.04$ when flying at higher altitudes if the gated distance is less than 300 feet below the aircraft so that the backscatter returns from atmospheric regions close to the aircraft are not eliminated.
3. Obviously, operating just at the borderline of the detection capabilities would not be desirable with regard to the residual contrast modulation; one would want to keep contrast modulation as high as possible in context with the actual inherent contrasts.
4. Hazy atmospheric conditions will occur frequently. For an unrestricted field-of-view and higher altitudes, distances of at least several hundred feet below the aircraft should be gated so that the contrast modulation received would be higher than $M_{rec} = 0.04$ from a target contrast of 2:1. In low to medium altitudes (several thousand feet) and restricted fields-of-view, the gating effect can largely be replaced by separation of the illuminating source from the receiver (15 feet or more); this has been done in many practical night photo activities to keep cost and complexity within acceptable limits.
5. For limited altitudes and restricted fields-of-view, good night photo capabilities have been achieved with active illumination by separating source and sensor sufficiently and adjusting beam divergence. This could not be done in missions requiring a larger field-of-view,

especially at low to medium altitudes and in those missions requiring good image contrast at long ranges or in missions conducted at higher altitudes with active light sources near the sensor. Larger fields-of-view can be covered and the range can be extended if gating capabilities are obtained at cost and complexity within the boundaries of an overall sensor program.

APPENDIX I

APPLIED TERMS, FORMULATIONS, AND DATA SOURCES

The observations discussed apply to limited ranges and altitudes with regard to the effectiveness and the need for gating of active illumination in night photographic systems. Altitude ranges of 2,000 to 23,000 feet have been compared previously in charts derived from radiative transfer investigations. It is generally known that the contrast ratio or contrast modulation between two adjacent objects or between an object and the background is significantly reduced by atmospheric backscatter. The contrast of the superposed spectral radiant incidence (E) received at the focal plane of a photographic system from the combined values of target radiance plus atmospheric backscatter radiance and from the background radiance plus the atmospheric backscatter radiance can be expressed as follows:

$$C_{\text{rec}} = \frac{E_T + E_a}{E_B + E_a} \quad (1)$$

where

- C_{rec} = Received apparent contrast ratio of target versus background.
- E_T = Spectral radiant incidence from the target.
- E_B = Spectral radiant incidence from the background.
- E_a = Spectral radiant incidence from the atmospheric backscatter.

Reference the geometry of a point source illumination (I_o) in Figure 21. In this displayed situation, the major contribution* to the superposed radiant incidence received by a sensor from the target/background area are compared and evaluated. In the photographic optical system, the radiant incidence (E) at the focal plane is:

$$E = \frac{\pi}{4(f/)^2} L \text{ or } E = \frac{\pi}{4(T/)^2} L \quad (2)$$

where

- L = Radiance of the individual target or scene area as seen at the entrance of the aperture of the optical system.
- $(f/)$ = f - stop.
- $(T/)$ = T - stop, if the optical transmission losses are to be included.

For the determination of contrast ratios, the lens-transmission can be cancelled for all practical purposes. The superposed radiant incidence (E) is received from the radiance (L) of the scene and that of the atmospheric path radiance in the line-of-sight. The received contrast ratio of target and background can be expressed as:

$$C_{rec.} = \frac{\frac{\pi}{4(f/)^2} \cdot L_T \cdot \tau_1 + \frac{\pi}{4(f/)^2} \cdot L_{(si)} \cdot \tau_2}{\frac{\pi}{4(f/)^2} \cdot L_B \cdot \tau_1 + \frac{\pi}{4(f/)^2} \cdot L_{(si)} \cdot \tau_2} \quad (3)$$

* Minor contributions and second order scattering effects of the atmosphere will not be significant with regard to the main objective of the compared situations, since the variations of the environmental statistical data are larger than the neglected minor contributions. Practical airborne experiments are made to provide additional statistical records with regard to frequently encountered atmospheric conditions.

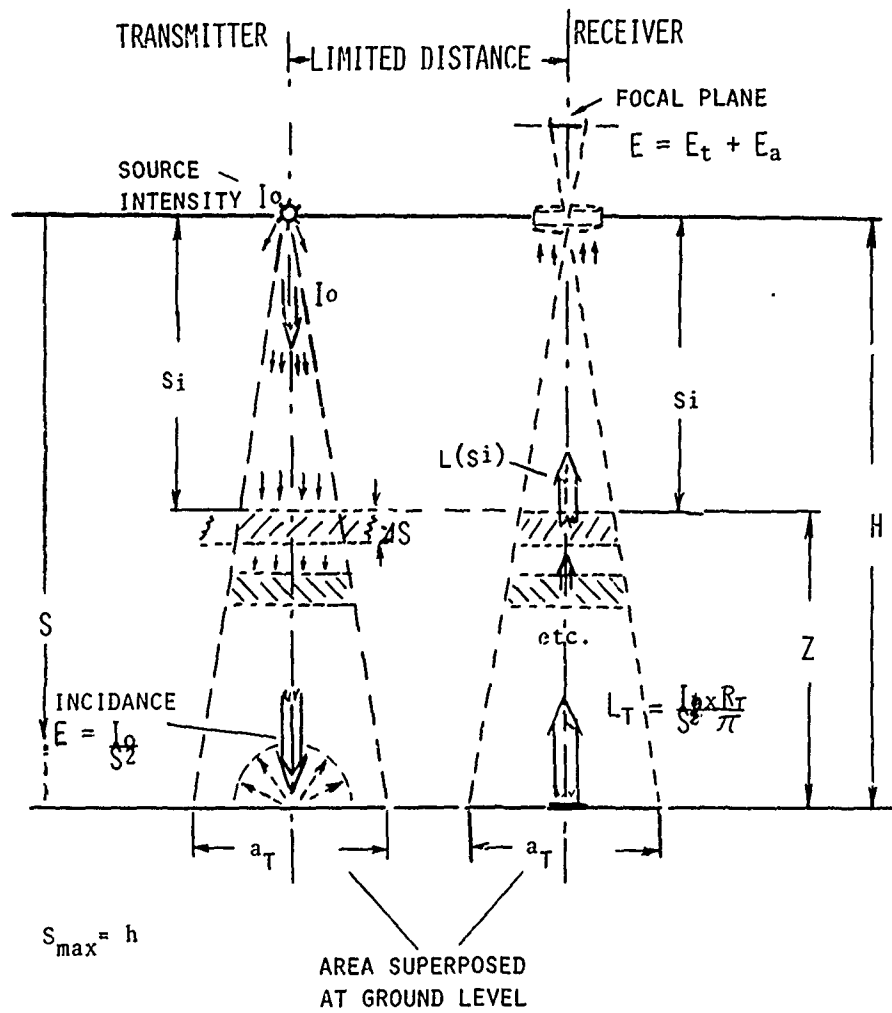


Figure 21. Point Source and Sensor Geometry and Symbols

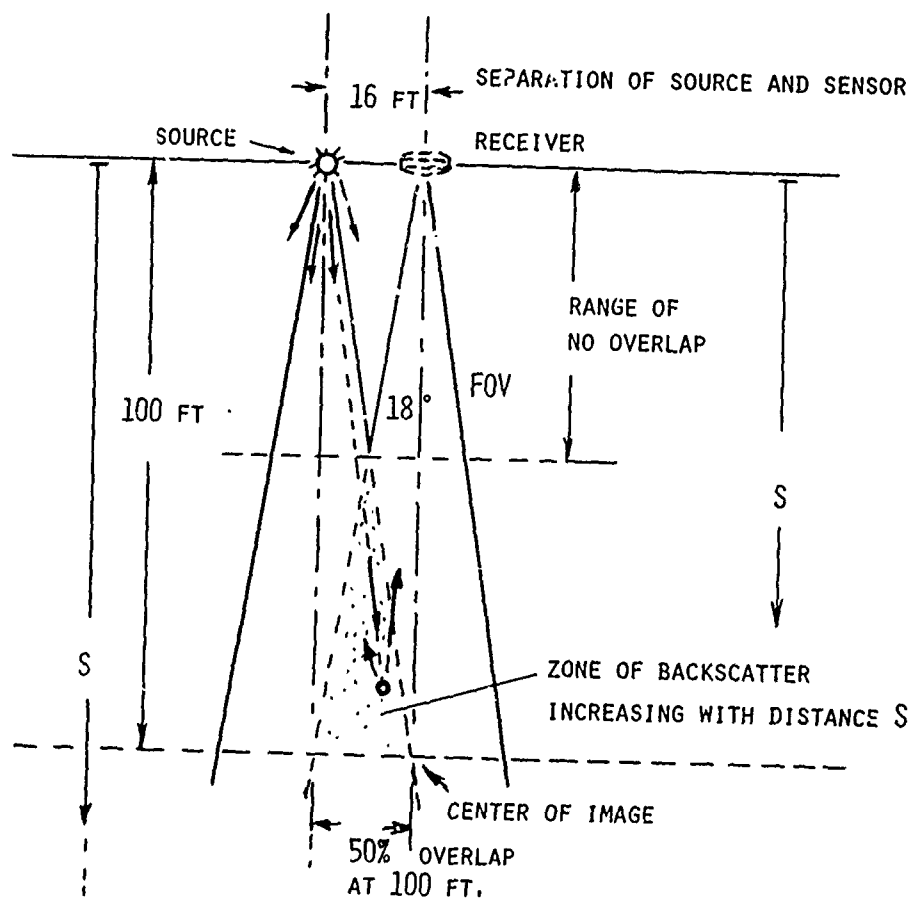


Figure 22. Source and Sensor Separation Partial Gating Results

where

L_T = Spectral radiance of the target.

L_B = Spectral radiance of the background.

$L_{(Si)}$ = Path radiance received from the atmospheric volume below the distance (Si) from the aircraft which was not eliminated by gating (Figure 20).

τ_1 = Atmospheric transmission with reference to scene distance.

τ_2 = Atmospheric transmission with reference to path radiance, a function of the gated distance (Si).

Contrast ratio terms may be modified showing explicitly the dependence on specific parametric factors of interest. Examples of such modified forms of contrast ratio are:

a.

$$C_{rec} = \frac{\frac{\pi}{4(f/f)^2}}{\frac{\pi}{4(f/f)^2}} \times \frac{L_T \cdot \tau_1 + L_{(Si)} \cdot \tau_2}{L_B \cdot \tau_1 + L_{(Si)} \cdot \tau_2} \quad (4)$$

$\left(\frac{\pi}{4(f/f)^2} \text{ Cancels itself} \right)$

b.

$$C_{rec} = \frac{C_0 + \frac{L_{(Si)} \times \tau_2}{L_B \times \tau_1}}{1 + \frac{L_{(Si)} \times \tau_2}{L_B \times \tau_1}} \quad (5)$$

where

$C_0 = \frac{L_T}{L_B}$ = Inherent contrast ratio at target area.

c. With reference to reflectance values of target (R_T) and background (R_B).

$$C_{\text{rec}} = \frac{C + \frac{L_{(si)}}{L_{100} \times R_B} \times \frac{\tau_2}{\tau_1}}{1 + \frac{L_{(si)}}{L_{100} \times R_B} \times \frac{\tau_2}{\tau_1}} \quad (6)$$

$$= \frac{R_T + \frac{L_{(si)}}{L_{100}} \times \frac{\tau_2}{\tau_1}}{R_B + \frac{L_{(si)}}{L_{100}} \times \frac{\tau_2}{\tau_1}}$$

where

L_{100} = Radiance of scene for 100% reflectance.

R_B = Background reflectance (diffuse).

R_T = Target reflectance (diffuse).

L_B = $L_{100} \times R_B$.

L_T = $L_{100} \times R_T$.

Radiance L_T and L_B are determined by the illumination source intensity (I_0) and the distance (S) of the scene from the source.

$$L_T = \frac{I_0 \cdot R_T}{S^2 \cdot \pi} \times \tau_{a_i} \text{ and } L_B = \frac{I_0 \cdot R_B}{S^2 \cdot \pi} \times \tau_a \quad (7)$$

The target radiance is a function of the square of the distance and is reduced by $\frac{1}{S^2}$ with the distance of the scene; in this case, this distance is the altitude of flight. The atmospheric path radiance $L_{(Si)}$, a function of the atmospheric optical criteria, is derived from statistical averages for various atmospheric conditions ranging from hazy (meteorological visibility 5 Km) to clear atmosphere (visibility 23 Km). The research results of the Air Force Cambridge Research Laboratory have been utilized (References 1 and 4).

The radiance of the atmospheric layers of the path at distances (S_i) beneath the aircraft, and the air volume below, down to the ground level, is determined by integrating the backscatter values of each unit of atmospheric volume within the path between the target area and sensor. First order scattering effects of the atmosphere will provide representative estimates regarding the relative results of gated versus nongated active photo systems.

The spectral wavelength of the illumination sources range from 0.7 to 0.9 micrometers and detailed attenuation coefficients per Km for the above spectral bands are listed in Reference 4. The data includes molecular absorption (K_m), molecular scattering σ_m , aerosol absorption (K_a), and aerosol scattering σ_a .

For a gated distance (S_i) and an incremental thickness of atmospheric layer $\Delta S = S - S_i$ the path radiance existing at the upper layer at distance (S_i) is:

$$L(S_i) = I_0 \int_{S_i}^S \frac{\beta' \cdot ds}{(S_i)^2} \quad (8)$$

For a limited air column thickness, the value of the back scatter factor β' may be approximated as a constant.

$$L(S_i) = I_0 \times \beta' \int_{S_i}^S \frac{ds}{(S_i)^2} = I_0 \beta' \left(\frac{1}{S_i} - \frac{1}{S} \right) \quad (9)$$

or for unit source intensity

$$\frac{L(S_i)}{I_0} = \beta' \left(\frac{1}{S_i} - \frac{1}{S} \right)$$

where

$L(S_i)$ = Path radiance.

β' = Backscatter factor, which is a function of altitude
 $Z = (h - S_i)$

Introducing the above values for L_T , L_B , and $L_{(Si)}$ into the contrast ratio term (C_{rec}) results in:

$$C_{rec} = \frac{\frac{\pi}{4(f/l)^2}}{\frac{\pi}{4(f/l)^2}} \times \frac{\frac{I_0}{S^2} \frac{R_T}{\pi} \cdot \tau_1 + I_0 \cdot \beta' \int_{Si} \frac{S dS}{(Si)^2} \times \tau_2}{\frac{I_0}{S^2} \frac{R_B}{\pi} \cdot \tau_1 + I_0 \cdot \beta' \int_{Si} \frac{S dS}{(Si)^2} \times \tau_2} \quad (10)$$

$$C_{rec} = \frac{R_T + \beta' \left(\frac{1}{Si} - \frac{1}{S} \right) \frac{\tau_2}{\tau_1} \cdot \frac{S^2 \pi}{1}}{R_B + \beta' \left(\frac{1}{Si} - \frac{1}{S} \right) \frac{\tau_2}{\tau_1} \cdot \frac{S^2 \pi}{1}}$$

The following terms are here recalled:

$$\beta' \left(\frac{1}{Si} - \frac{1}{S} \right) = \frac{L_{(Si)}}{I_0} \text{ and } \frac{1}{S^2 \pi} = \frac{L_{100}}{I_0} \quad (11)$$

Since in all terms for contrast ratio and modulation the source intensity (I_0) is cancelled, the computation for atmospheric backscatter radiance ($L_{(Si)}$) and target radiance (L_T and L_B) can be made for unit source intensity. Reference 4 gives data and calculations of the estimated path radiance ($L_{(Si)}$), the atmospheric transmission τ_1 and τ_2 applied to the received target/background radiance, and the path radiance.

Stepwise integration is applied for long ranges (high altitudes), where atmospheric optical properties are subject to significant changes as a function of altitude. The relevant backscatter factor β'_h is determined from the tables of the above reports for each step of the incremental air column.

With regard to the path radiance,

$$L(S_i) = \beta' \left(\frac{1}{S_i} - \frac{1}{S} \right) \times I_0 \quad (12)$$

an accepted value for β' is

$$\beta' = .12\sigma_m + 0.03\sigma_a \text{ per km} \quad (13)$$

The terms are extracted from the angular scattering function $F(\theta)$:

$$F_m(\phi) + F_a(\phi) \quad (14)$$

discussed in Reference 4. σ_m and σ_a are average values at each altitude $Z = h - S_i$ and intervals $\Delta S = S - S_i$. The received path radiance reduced by the transmission τ_2 is expressed in the product:

$$\begin{aligned} L(S_i)_{\text{rec}} &= I_0 \cdot \beta' \cdot \left[\frac{1}{S_i} - \frac{1}{S} \right] \times \tau_2 \\ &= L(S_i) \cdot \tau_2 \end{aligned} \quad (15)$$

τ_2 depends on the path length (S_i) and its total atmospheric attenuation γ^T throughout the relevant altitude intervals.

$$\tau_2 = e^{-2\gamma^T \times \Delta(S_i)} \quad (16)$$

$$\gamma_{\text{per km}} = K_m + \sigma_m + k_a + \sigma_a \quad (17)$$

$$\gamma \times \Delta Z = (K_m + \sigma_m + k_a + \sigma_a) \times \Delta Z \quad (18)$$

$$\text{and } \gamma^T \times \Delta(S_i) = (\gamma_{0-1} + \gamma_{1-2} + \dots + \gamma_{(h-1)-h}) \times \Delta(S_i) \quad (19)$$

for altitude zones $h - Z = S_i$

$$\gamma_{(h-1)} + \gamma_{(h-2)-(h-1)} + \gamma_{(h-3)-(h-2)} + \dots \Delta(S_i) = S_i \times \gamma_{\text{mean}} \quad (20)$$

Because the illumination source is located at the receiver altitude (see Figure 21) the transmission factor τ must account for the two-way range, requiring the factor "2" in the exponential term for

$$\tau = e^{-2\gamma^T \Delta(Si)} \quad (21)$$

The transmission (τ_1) from the ground level for target and background radiance is a function of flight altitude (h) only while the transmission τ_2 changes with the gated distance (Si) and altitude (h). In the context of this report:

$$\tau_1 = e^{-2\gamma^T \Delta h} \quad (22)$$

$$\text{if } \gamma^T = \gamma_{0-1} + \gamma_{1-2} + \dots + \gamma_{(h-1)-h}$$

The term received contrast ratio ($C_{rec} = \frac{E_T}{E_B}$) of radiant incidence and the term contrast modulation (received) $M_{rec} = \frac{E_T - E_B}{E_T + E_B}$ are interrelated in equation:

$$M_{rec} = \frac{C_{rec} - 1}{C_{rec} + 1} \quad (23)$$

where

C_{rec} = Contrast ratio of received radiant incidence.

M_{rec} = Contrast modulation of received radiant incidence.

In the previous section of this report the comparison of gated and nongated situations is primarily expressed in terms of contrast modulation (M_{rec}) which can be written in a variety of forms in the same manner as it was done for the contrast ratio. Appendix 1 lists a number of modified terms expressing the received contrast modulation (M_{rec}) as a function of the target/background radiances or reflectivities and atmospheric backscatter (path radiance) values. Any of these terms may be selected in accordance with the specific parametric dependence which needs to be studied. Contrast modulation and its dependence on

frequently experienced target and background reflectances is expressed by:

$$M_{\text{rec}} = \frac{R_T - R_B}{R_T + R_B + 2 \frac{L(\text{Si}) \times \tau_2}{L_{100} \times \tau_1}} \quad (24)$$

or:

$$M_{\text{rec}} = \frac{M_0}{1 + \frac{L(\text{Si})}{L_{100} \times \frac{R_T + R_B}{2}} \times \frac{\tau_2}{\tau_1}} = \frac{M_0}{1 + \frac{L(\text{Si})/l_0}{L_{100} \times l_0 \times R_{\text{mean}}} \times \frac{\tau_2}{\tau_1}} \quad (25)$$

where

$M_0 =$ = Inherent contrast modulation.

$\frac{R_T + R_B}{2} =$ R mean of target scene.

The strongest improvement rate of contrast modulation with the change of gated distances (Si) occurs at altitudes close to the aircraft. This has been shown in the graphic displays and the discussion in Section II. In those regions the integration was accomplished in sufficiently small steps (100 ft), such that errors related to the method of integration are negligibly small.

Integration in steps permits us to use the atmospheric optical properties from the referenced reports. A completely automated integration requires the proper transformation of the tabular data into an approximated continuous function and furthermore leads to a relatively complex integral. The development of more complex mathematical terms of this nature was not made a part of this study.

APPENDIX II CONTRAST MODULATION TERMS

Modified forms of contrast-modulation as received by a sensor are listed in context with the terms given in the glossary of symbols.

$$C_{\text{rec}} = \frac{C_0 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}}{1 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}} \quad (1)$$

$$M_{\text{rec}} = \frac{C_{\text{rec}} - 1}{C_{\text{rec}} + 1} = \frac{\frac{C_0 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}}{1 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}} - 1}{\frac{C_0 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}}{1 + \frac{L_{\text{si}} \tau_2}{L_{\text{B}} \tau_1}} + 1} \quad (2)$$

$$C_0 = \frac{R_{\text{T}}}{R_{\text{B}}}$$

Reduced forms:

$$M_{\text{rec}} = \frac{C_0 - 1}{C_0 + 1 + 2 \frac{L_{\text{si}} \tau_2}{L_{100} \times R_B \tau_1}} \quad (3)$$

$$M_{\text{rec}} = \frac{R_T - R_B}{R_T + R_B + 2 \times \frac{L_{\text{si}} \tau_2}{L_{100} \tau_1}} \quad (4)$$

$$M_{\text{rec}} = \frac{\frac{\Delta R}{2}}{R_{\text{mean}} + \frac{L_{\text{si}} \tau_2}{L_{100} \tau_1}} \quad (5)$$

$$M_{\text{rec}} = \frac{M_0}{1 + \frac{L_{\text{si}} \tau_2}{L_{100} \times R_{\text{mean}} \tau_1}} = \frac{M_0}{1 + \frac{L_{\text{si}}}{I_0} \times \frac{I_0}{L_{\text{mean}}} \times \frac{\tau_2}{\tau_1}} \quad (6)$$

where

L_{si} = Path radiance for atm. layer starting at distances S_i and beyond, down to ground level.

L_{100} = Object reflectance 100% (radiance value).

Normalized to unit source intensity, $\frac{L_{\text{si}}}{I_0}$ and $\frac{L_{100}}{I_0}$ = Radiance per unit source intensity.

From Appendix I Equation 9 insert:

$$\frac{L(s_i)}{I_0} = \beta' \left[\frac{1}{S_i} - \frac{1}{S} \right] \text{ and } \frac{L_{100}}{I_0} = \frac{1}{S^2 \pi} \text{ in}$$

in Equation 6

$$M_{\text{rec}} = \frac{I_0}{1 + \beta' \left[\frac{1}{S_i} - \frac{1}{S} \right] \times \frac{S^2 \pi}{R_T + R_B} \times \frac{\tau_2}{\tau_1}} \quad (7)$$

$$M_{\text{rec}} = \frac{R_T - R_B}{R_T + R_B \times 2 \times \beta' \left[\frac{1}{S_i} - \frac{1}{S} \right] \times \frac{S^2 \pi}{1} \times \frac{\tau_2}{\tau_1}} \quad (8)$$

$$\frac{R_T}{R_B} = C_0$$

$$M_{\text{rec}} = \frac{C_0 - 1}{C_0 + 1 + 2 \beta' \left[\frac{1}{S_i} - \frac{1}{S} \right] \frac{S^2 \pi}{1 \times R_B}} \quad (9)$$

Data for various atmospheric conditions can be found in the References and other reports. Elaborate computer programs regarding atmospheric transmission and scattering have been developed by the Optical Physics Laboratory of the Cambridge Research Laboratories and at other organizations, and these programs can be applied if exploration

of a large number of specific situations is required. The listed relations are not intended as a substitute for any other program which includes atmospheric parameters.

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